The Scientific Basis of Modern Meteorology

By C. G. Rossby [1]

IN SEVERAL SCIENCES on which agriculture is closely dependent there have been striking developments in recent decades, and these have resulted in rapid progress of great benefit to mankind. Genetics, soil science, and nutrition have all made great strides based on important fundamental discoveries. Latest to join this group is meteorology. Here is a semi-technical presentation of the physical basis of this science as it has been developed since the last great war.

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THE SCIENCE of meteorology does not yet have a universally accepted, coherent picture of the mechanics of the general circulation of the atmosphere. This is partly because observational data from the upper atmosphere still are very incomplete, but at least as much because our theoretical tools for the analysis of atmospheric motions are inadequate. Meteorology, like physics, is a natural science and may indeed be regarded as a branch of the latter; but whereas in ordinary laboratory physics it is always possible to set up an experiment, vary one factor at a time, and study the consequences, meteorologists have to contend with such variations as nature may offer, and these variations are seldom so clean-cut as to permit the establishment of well-defined relationships between cause and effect.

Under these conditions theoretical considerations become more important than ever. The atmosphere may be considered as a turbulent fluid subjected to strong thermal influences and moving over a rough, rotating surface. As yet no fully satisfactory theoretical or experimental technique exists for the study of such fluid motions; yet it is safe to say that until the proper theoretical tools are available, no adequate progress will be made either with the problem of long-range forecasting or with the interpretation of past climatic fluctuations.

Certain phases of the admittedly oversimplified analysis of the circulation of the atmosphere presented in this article may be traced as far back as 1888, to the German physicist Von Helmholtz, but other parts are the result of recent research and should, to some extent, be considered as the author's personal view. The combination of these various elements into a still fairly crude bird's-eye view of the atmosphere and its circulation was undertaken during the last 4 or 5 years as a byproduct of an intensive study of Northern Hemisphere weather, with which the author had the good fortune to be associated. This study was conducted as a cooperative project between the United States Department of Agriculture and the Massachusetts Institute of Technology and was to a large extent supported by Bankhead-Jones funds. A brief historical outline of the development of the theory will be found at the end of the article.

CONVECTIVE CIRCULATION

The energy that drives the atmosphere is obtained from the sun's radiation. Just outside the atmosphere an area exposed at right angles to the sun's rays would receive radiant energy at the rate of about 2 gram-calories per square centimeter per minute. The earth is approximately spherical, and its surface area is therefore four times as large as the cross-section area intercepting the sun's rays; it follows that on an average each square centimeter at the outer boundary of the atmosphere receives about one-half of a gram-calorie per minute. Part of this radiation is reflected back to space from the upper surface of clouds in the atmosphere, and part is lost through diffuse scattering of the solar radiation by air molecules and dust. It is estimated that a total of about 40 percent on an average is lost through these processes. (It is this reflection that determines the whiteness, or albedo, of the earth as a planet, and thus the earth is said to have an albedo of about 40 percent.) The remaining radiation passes through the atmosphere without much absorption and finally reaches the surface of the earth, where it is absorbed, generally without much loss through reflection. Snow surfaces furnish an important exception, since they may reflect as much as 80 percent of the incident solar radiation.

Since the mean temperature of the earth does not change appreciably, it follows that the heat gained from the sun must be sent back to space. In the surface of the earth the solar radiation is transformed into heat, and this heat is returned as "long"—infrared—radiation toward space. The rate at which the ground sends out such radiation is very nearly proportional to the fourth power of the absolute temperature. Thus, at 10° C. the heat loss of the ground through radiation is about 15 percent greater than at freezing, and it follows that the surface temperature of the earth must increase if the incident solar radiation increases, to maintain equilibrium between radiation income and loss. The ground is very nearly a perfect radiator, that is, it sends back to the atmosphere and to space the maximum amount obtainable from any surface at a particular temperature.

All the invisible radiation from the ground cannot escape to space; the larger part of it is absorbed in the atmosphere, principally by the water vapor in the lower layers, but also to some extent by small amounts of ozone present in the upper atmosphere. The atmosphere in turn emits infrared (heat) radiation upward and downward. The radiation emitted in either direction increases with the mean temperature of the atmospheric column but is always less than the radiation emitted by a perfect radiator of the same temperature. The more perfectly the atmospheric column absorbs the ground radiation from below, the more perfectly it radiates. It is evident that if radiative processes alone controlled the behavior of the atmosphere it would have to emit as much as it absorbs. Since it emits in two directions but absorbs appreciably only from the ascending ground radiation, it follows that the mean temperature of the atmosphere must be lower than that of the ground. Also, since the ground receives not only solar radiation but also infrared radiation from the atmosphere, the ground temperature must be higher than might be expected from the intensity of the incident solar radiation alone.

The preceding analysis shows that the atmosphere serves as a protective covering which raises the mean temperature of the surface of the earth. This is often referred to as the "greenhouse" effect of the atmosphere. The analysis also shows that the atmosphere as a whole must be colder than the ground. The reasoning may be refined by considering the atmosphere as consisting of a number of superimposed horizontal layers, and it may then be shown that the mean temperature must decrease upward from layer to layer, fairly rapidly near the ground, then more and more slowly. At great heights (above 10 kilometers, or 6 miles) the temperature becomes very nearly constant. This layer is called the stratosphere.

Up to this point our analysis has been based on the assumption that no appreciable direct absorption of solar radiation occurs in the atmosphere. This is approximately correct as far as the lowest 20 kilometers (12 miles) of the atmosphere are concerned. However, between approximately 20 to 50 kilometers (12 to 30 miles) above the ground the atmosphere contains a certain amount of ozone, increasing from the Equator to high latitudes, and this ozone is capable of directly absorbing some of the radiation emitted by the sun and also, to a somewhat lesser extent, part of the long-wave radiation from below. As a result, in the upper portions of this ozone layer the air temperature appears to exceed the mean air temperature next to the ground. It is this ozone layer which protects us from the extreme ultraviolet rays in the sun's radiation.

At still higher levels the oxygen and the nitrogen in the earth's atmosphere are capable of intense direct absorption of solar radiation. For this and other reasons, it is now generally believed that the temperature again rises to values which may be as high as 500° to 1,000° Abs. above 150 kilometers (93 miles) above sea level.

This uppermost region of high temperature is located at a height where the air density is so small that no appreciable direct dynamic effect on air circulation in the lower layers of the atmosphere can be expected. It is necessary to admit, however, that temperature variations and resulting circulation at the ozone level may be significant so far as weather and wind in the lowest strata are concerned. No existing theory suggests a definite mechanism for control of sea level circulation and weather by an ozone layer. On the other hand, circulation in the lowest 20 kilometers of the atmosphere has definitely been shown to produce redistributions of the ozone aloft, and hence atmospheric ozone has of late become an element of decided interest even to practical meteorologists, as a means of tracing air movements in the stratosphere.

Until our knowledge of the absorption and emission of radiation by water vapor increases, it is not possible to state what the final decrease of temperature with elevation would be in case of purely radiative equilibrium, but it is probable that in the lowest portion of the atmosphere it would be far steeper than the decrease actually observed (about 6° C. in 1 kilometer, or 17° F. in a mile). As a result of evaporation, the lowest layers would be very nearly saturated with water vapor. It can be demonstrated that a saturated atmosphere in which the decrease in temperature with elevation is more rapid than the value just indicated must be mechanically unstable or, allowing for its compressibility, top-heavy, and thus must tend to turn over. Violent vertical currents (convection) would result, which would carry water vapor and heat from the earth's surface to higher levels.

At these upper levels the water vapor would condense as the result of expansion cooling, and from there the heat realized through the condensation processes would be sent out to space through infrared radiation. In this way the free atmosphere would actually give off more heat by radiation than it would absorb, and the loss would be balanced by convective transport of latent heat upward. Thus an atmosphere heated uniformly from below in all latitudes and longitudes—that is, the atmosphere of a uniformly heated nonrotating globe—would show no sign of organized circulation between different latitudes but would be characterized by violent convection somewhat like that in a kettle of water which is being heated from below.

Rising bodies of air expand with decreasing air pressure and cool as the result of the expansion. In the convectively unstable atmosphere here described, the ascending currents would acquire their momentum in the overheated layers next to the ground and rise beyond the level where they reach temperature equilibrium with the

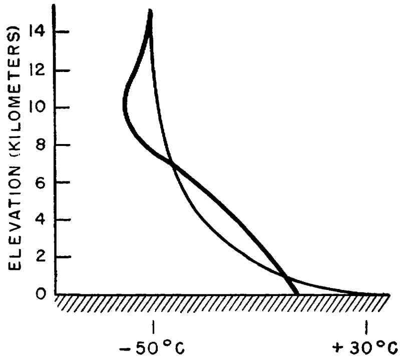

FIGURE 1.—The thin line shows how the temperature would drop with height if radiation alone controlled the state of the atmosphere. This is an unstable arrangement resulting in violent overturning. The heavy line shows the result—cooling next to the ground, a moderate temperature drop with elevation in the lower atmosphere (troposphere), then a marked temperature minimum (tropopause), and above that an almost constant temperature.

environment. As a result of this overshooting, a layer of minimum temperature would be created at the top of the lower, convective portion of the atmosphere (the troposphere). It follows that troposphere and stratosphere would be separated by a narrow transition zone (tropopause) of rapid temperature increase upward. The effect of convection on an unstable temperature distribution assumed to have been established by radiation is shown in figure 1. Figure 2, *A*, shows the convective circulation of the troposphere on a uniformly heated nonrotating globe, as described.

MERIDIONAL (NORTH-AND-SOUTH) CIRCULATION

Into this chaotic state a certain order is brought through the fact that the incoming solar radiation is far from uniformly distributed over the surface of the earth. Because of the low angle of incidence of solar radiation in polar regions, a given horizontal area in high lati-

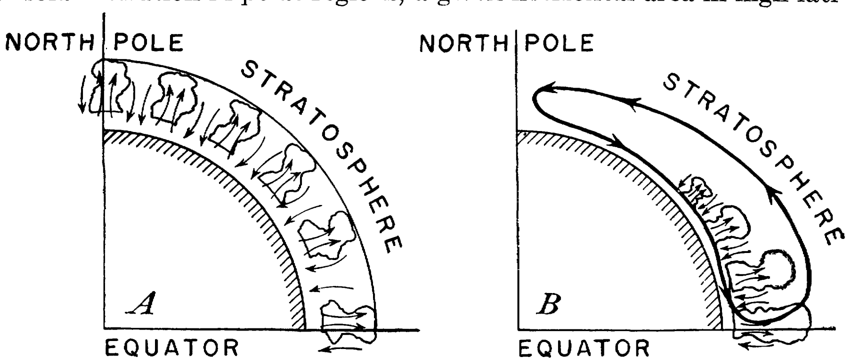

FIGURE 2.—Schematic diagrams illustrating *A*, the heavy, irregular convective activity, accompanied by cumulus and thunderstorm clouds, that would characterize the atmosphere if the sun's heat were applied uniformly everywhere and the earth did not rotate; *B*, concentration of convection in the vicinity of the Equator, north winds near the ground and south winds aloft, which would result on a nonrotating earth with the sun's heat applied mainly in low latitudes, as it actually is on the rotating earth.

tudes receives far less solar radiation than an equal area closer to the Equator. To determine the consequences of this concentration of heat income in equatorial regions, it is advisable for a moment again to disregard the rotation of the earth and investigate what would happen if the earth stood still but the sun followed its normal path across our sky. In response to the greater heat income in low latitudes, the temperature there would rise until the increased temperature of the atmosphere in this region would result in increased infrared radiation toward space, capable of reestablishing complete balance with the heat received from the sun. Such an equilibrium corresponds to a far greater increase from Pole toward Equator in surface temperature or in the temperature of the lower atmosphere than is actually observed. As a result of this heating of the atmosphere in low latitudes, the air there would expand vertically, while the cooling in high latitudes would result in a vertical shrinking.

Thus, at a fixed level of, say, 5 kilometers (3 miles) above sea level, a greater portion of the total atmospheric air column would be found overhead near the Equator than near the Poles. Since the air pressure always measures the weight of the superimposed air column, it follows that higher pressure would prevail at the 5-kilometer level near the Equator than near the Poles. Air, like any fluid, tends to move from high to low pressure, and thus the upper atmosphere would be set in motion from the Equator polewards. This motion obviously would raise the sea level pressure near the Poles and reduce it near the Equator, and as a result the surface air would move from Poles toward Equator.

Considering the Northern Hemisphere only, it is thus evident that the inequality in heat income between latitudes produces, on a nonrotating globe, south winds aloft and north winds below. This circulation scheme is illustrated in figure 2, *B*. Relatively warm air is carried northward aloft and relatively cold air is carried southward near the ground. As a result, it is no longer necessary for the ground and the sea surface in low latitudes to reradiate all the local radiation income to space, but part of this heat is used up in evaporation and is transported northward and upward in the form of latent and realized heat. It is finally returned to space from higher latitudes or higher elevations through infrared radiation.

Thus a vertical column of air in high latitudes no longer absorbs as much radiation as it emits but is continually suffering a net loss of heat through the combined effects of the various radiative processes. This loss is balanced by a gain of heat (realized or latent) resulting from the exchange of air with more southerly latitudes and by a gain resulting from realization of latent heat through condensation. Even though our present knowledge of the radiative processes in the atmosphere is still very incomplete, it is becoming increasingly probable that everywhere in high and middle latitudes the free atmosphere above a shallow layer of air next to the ground is constantly losing heat by radiation. The significance of water vapor as a carrier of heat (latent) poleward and upward is, for the same reason, becoming more and more appreciated.

As a result of the net transport of heat poleward the temperature contrast between Pole and Equator is reduced.

The poleward flow of warm air aloft and the transport toward the Equator of relatively cold air next to the ground has the further effect of bringing about a reduction in the vertical temperature decrease. Thus instability is cut down and vertical convection reduced in middle and high latitudes.

The picture thus obtained, that of an atmosphere heated from below and rising near the Equator, chilled and sinking in higher latitudes, requires a few additional comments to eliminate possible misunderstandings. Even in high latitudes the temperature decreases upward. Thus, if the air in these regions is steadily sinking, the individual air particles must be getting warmer, which would hardly seem to be in accord with the idea that the air in this region is losing heat through radiation. It must be remembered, however, that air is highly compressible. As the air sinks it comes under the influence of higher pressure. Owing to the compression its temperature rises, just as the temperature of a gas in a cylinder rises with compression. In the atmosphere, the rate at which the temperature of a sinking particle would rise as a result of compression is about 10° C. in 1 kilometer. Thus, if the temperature of a sinking air particle rises only 6° C. in 1 kilometer, it means that the particle has given off heat corresponding to a temperature drop of about 4° C. Dry air, rising through the atmosphere, cools through expansion at the same rate, 10° C. in 1 kilometer. Thus if a rising current shows a temperature drop of only 6° C. per kilometer, heat must have been added, corresponding roughly to a temperature increase of 4° C. per kilometer. If this additional amount of heat is not available, the temperature at fixed upper levels would obviously drop.

In saturated air, rising through the lower atmosphere, a certain amount of heat is made available through the condensation of the water vapor carried along by the current. Thus the expansion cooling of saturated air is less intense than the expansion cooling of dry air. The actual rate of cooling varies, but it amounts to about 6° C. per kilometer in the lower atmosphere for temperatures around freezing.

The circulation described above between a heat source in low latitudes and at low elevations and a cold source in middle and higher latitudes but distributed over all elevations works on the same principle as a simple heat engine. In such an engine the difference between the heat received at the heat source and the heat given off at the cold source is converted into work. Here it appears as kinetic energy of the wind system. Unless brakes are applied, the wind must constantly increase in speed. Such brakes are provided by the friction between the winds and the ground (or sea surface). Since no appreciable changes are wrought in the surface of the earth, the energy of the winds is steadily converted into heat, which ultimately must be radiated back to space. Thus, in the final analysis, the total amounts of radiation received and given off by the planet Earth must equal each other.

The scheme just outlined differs sharply from the true situation observed in the atmosphere, and this discrepancy depends mainly on two factors completely neglected up to the present time. The first of these is the rotation of the earth; the second the distribution of continents and oceans. The effect of the rotation will be discussed first, the earth's surface still being considered as uniform.

INFLUENCE OF THE EARTH'S ROTATION

The earth does not appreciably change its speed of rotation, and thus it may be assumed that on an average it neither receives momentum from nor gives off momentum to the atmosphere. The rotation, however, does profoundly affect the character of the flow patterns observed in the atmosphere.

To understand the influence of the earth's rotation, consider first this simple experiment: If a marble attached to a piece of string is placed on top of a smooth table and swung around the free end of the string and if then the length of the string is shortened, it will be found that the speed of the marble increases. If the string is shortened to one-half its original length, the speed of the marble is doubled; if the string is reduced to one-third its original length, the speed of the marble is tripled. Thus the product of speed and radius of rotation remains constant during the experiment. This product is usually referred to as the angular momentum (per unit mass) of the marble.

A ring of air extending around the earth at the Equator, at rest relative to the surface of the earth, spins around the polar axis with a speed equal to that of the earth itself at the Equator. If somehow this ring is pushed northward over the surface of the earth, its radius is correspondingly reduced; and it follows from the principle set forth that the absolute speed of the ring from west to east increases. Since the speed of the surface of the earth itself from west to east decreases northward, it follows that the moving ring, in addition to its northward velocity, must acquire a rapidly increasing speed from west to east relative to the earth's surface.

The principle itself may be illustrated very simply by an extreme and absurd case. The eastward speed of the earth itself at the Equator is about 465 meters (509 yards) per second. A ring of air displaced from this latitude to latitude 60, where the distance from the axis of the earth is only half that at the Equator, would appear in its new position with double the original absolute velocity, or 930 meters (1,017 yards) per second. Since the speed of the earth itself at this latitude is only half what it is at the Equator, or 232 meters (254 yards) per second, it follows that a ring of air thus displaced would move eastward over the surface of the earth with a relative speed of 698 meters per second (about 1,560 miles per hour). Obviously such wind speeds never occur in the atmosphere, one reason being the effect of frictional forces, another the fact that large-scale atmospheric displacements never are symmetric around the earth's axis or as large as those indicated.

It is apparent, however, that this tendency toward the establishment of west winds in northward-moving rings of air and of east winds in southward-moving rings must modify the previously described meridional (north-south) circulation scheme considerably. This is best seen if one assumes that the meridional circulation scheme characteristic of a nonrotating earth (fig. 2, *B*) is suddenly set in operation on a rotating earth in which the atmosphere previously was at rest relative to the ground. The moment the circulation begins, west winds (relative to the earth) would begin to develop in the upper atmosphere, with a slight component northward, and east winds in the lower atmosphere, with a slight component southward.

In this scheme ground friction plays a basic role, since it prevents the development of excessive east winds in the surface layers. The upper atmosphere, in which west winds prevail, is not in direct contact with the earth's surface; however, mixing of air between the upper and lower strata must reduce the west winds aloft as well as the east winds below. Since the momentum of the east winds also is reduced from below, through the effect of ground friction, it is apparent that the mass of the west winds aloft would far exceed the mass of the easterlies near the surface. Figure 3, *A*, illustrates what the velocity distribution would be a short time after the rotation began.

Certain features of this picture agree well with observed conditions. Above 4 or 5 kilometers (2½ to 3 miles), westerly winds prevail in all latitudes. At sea level, easterly wind components are normally observed between latitude 30° N. and 30° S. Other belts of easterly wind components are observed in the polar regions, north of latitude 60° N. and south of latitude 60° S. Unexplained, however, is the fact that in each hemisphere westerly winds prevail also at sea level within a broad belt between latitudes 30° and 60°, approximately.

It is fairly easy to see that the theoretical model in figure 3, *A*, characterized by east winds everywhere in the surface layers, is physi-

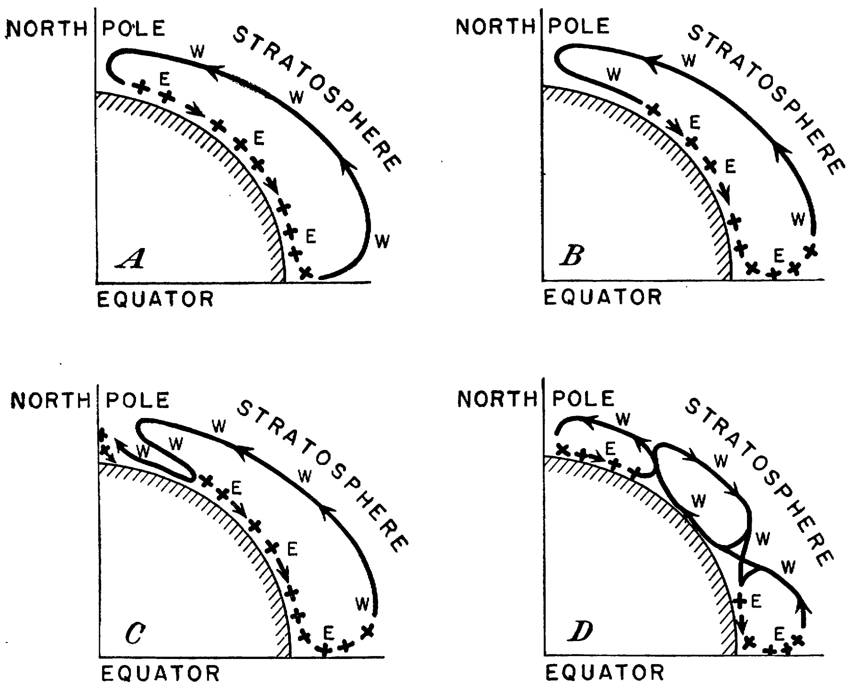

Figure 3.—Why the earth's rotation leads to a break-down into several cells of the simple meridional (north-south) circulation represented in figure 2, *B*. *A*, A short time after the meridional circulation indicated by the arrows is set in operation, west winds appear aloft, east winds below. *B*, Gradually the upper west winds are brought down to the ground near the Pole, and the east winds rise near the Equator. *C*, The west winds are retarded by friction and seek their way northward, but cooling and sinking continue next to the Pole. Finally, *D*, a complete three-cell circulation system develops.

cally impossible as a steady state. If east winds prevailed in all latitudes, friction between the atmosphere and the solid earth would constantly tend to reduce the rotation of the earth. On the other hand, the atmosphere would constantly gain momentum from the earth. Sooner or later a state of equilibrium would be established in which the atmosphere would neither gain nor lose momentum through contact with the earth—an equilibrium which is known to prevail, since the rotation of the earth for practical purposes can be regarded as constant. Such an equilibrium requires that the retarding influence of the east winds must be offset by the accelerating influence of a belt or belts of west winds, also in the surface layers. It is clear, however, that this argument is incapable of determining the number, width, and strength of the required west-wind belts. It is the purpose of the four diagrams in figure 3 to explain why the initial meridional circulation, under the influence of the earth's rotation, necessarily must break down into at least three separate cells on each hemisphere.

In order to understand the successive stages of development indicated in figure 3, it is first necessary to discuss, in some detail, the effect of the rotation of the earth on the relative motion of air over its surface. Wherever a ring of air parallel to a latitude circle is rotating more rapidly than the surface of the earth itself, it is acted upon by an excess of centrifugal force which tends to throw the ring away from the axis of the earth, which in the Northern Hemisphere means southward.[2] If the ring rotates with the same speed as the earth (that is, if it is at rest relative to the surface of the earth) this excess of centrifugal force vanishes. If this were not the case, any object resting on the surface of the earth would be thrown toward the Equator. A ring of air rotating more slowly than the earth itself, and hence appearing as an east wind relative to the earth, suffers from a deficiency in centrifugal force and tends to move toward the axis of the earth, that is, in this hemisphere, toward the north. To keep a west-wind belt from being thrown southward, the atmospheric pressure must be higher to the south than to the north of the ring (in the Northern Hemisphere), thus producing a force directed northward and capable of balancing the excess centrifugal force. If no such pressure force (gradient) is available, the ring will be displaced slightly southward until enough air has piled up on its south side to bring about the required cross-current pressure rise to the south and equilibrium. The total displacement needed for this purpose is usually quite small as compared with the width of the current.

To keep an east-wind belt in equilibrium, the atmospheric pressure must be higher on the north side than on the south side (in the Northern Hemisphere), so that the resulting pressure force balances the deficiency in centrifugal force acting on the ring. It has already been brought out that in the Northern Hemisphere air moving northward tends to acquire a velocity eastward, while air moving southward tends to acquire velocity westward. To offset this tendency toward deflection eastward,[3] a north-bound current of limited width piles up

[2] That part of the centrifugal force (per unit mass) which corresponds to the earth's own rotation is balanced by a component of the earth's gravitational attraction. The resultant of this component of the centrifugal force and of the earth's total true gravitational attraction is perpendicular to the earth's surface and constitutes what is normally referred to as gravity.

[3] The method of compensation here described is obviously impossible for circumpolar rings of air. Hence rings of air displaced northward acquire west-wind tendencies, south-bound rings east-wind tendencies, as brought out previously.

air to the east and creates higher pressure to the east than to the west, while the reverse applies to a south-bound current.

All these results may be generalized so as to apply to any wind direction. It is thus found that in the Northern Hemisphere steady winds always blow in such a fashion that the air pressure drops from right to left across the current for an observer facing downstream. The stronger the current flows, the steeper the drop in cross-current pressure. If, in any horizontal plane, lines of constant air pressure (isobars) are drawn, it may be seen that the air follows the isobars and moves counterclockwise around regions of low pressure (cyclones) and clockwise around regions of high pressure (anticyclones). In the Southern Hemisphere, the direction of motion around highs and lows is reversed.

It is apparent from the preceding reasoning that the relationship between wind and horizontal pressure distribution is truly mutual; a prescribed pressure distribution will gradually set the air in motion in accordance with the law set forth; likewise, if somehow a system of horizontal currents has been set up in the atmosphere, the individual current branches will very quickly be displaced slightly to the right (in the Northern Hemisphere) until everywhere the proper cross-current pressure drop from right to left has been established. Owing to the ease with which the atmosphere thus builds up the cross-current pressure drop required for equilibrium flow, the reasoning just outlined merely helps in understanding why the pressure in the Northern Hemisphere always rises from left to right for an observer looking downstream but does not by itself indicate that one current pattern is more likely to be established than another. To establish the character of the current patterns, either the pressure distribution must be known, or additional physical principles must be utilized.

It is now possible to return to a discussion of the circulation development in figure 3. In an axially symmetric atmosphere, such as the one here discussed, the absolute angular momentum of individual parcels of air does not change except through the influence of frictional forces. Under these conditions it is evident that the meridional (north-south) movements indicated in figure 3, *A*, must gradually redistribute the absolute angular momentum so as to create west winds next to the ground in the polar regions, and east winds aloft over the Equator. This is the state illustrated in figure 3, *B*. If the meridional circulation is slow, the pressure distribution in the atmosphere must constantly adjust itself fairly closely to the prevailing zonal winds. Thus, in figure 3, *B*, there would be a sea-level-pressure maximum at the transition point between the east winds in low latitudes and the west winds farther north. This latter belt of west winds can continue its southward displacement only as long as it is acted upon by an excess of centrifugal force. However, part of the air in this west-wind belt must steadily lose momentum through frictional contact with the ground. Under the influence of the resulting deficiency in centrifugal force this shallow portion of the belt next to the earth's surface must seek its way northward, as indicated in figure 3, *C*. Since air continues to cool and sink next to the Pole, it follows that the retarded west winds, for purely dynamic reasons, are forced to escape aloft some distance from the Pole. Finally a cellular state develops, as indicated in figure 3, *D*.

The Three Hemispheric Circulation Cells

Up to this point the break-down of the original simple meridional circulation scheme has been treated as a purely dynamic effect. It now becomes necessary to investigate whether the final mean circulation scheme is compatible with the thermal processes of the atmosphere. For this purpose we must fall back upon our as yet very incomplete knowledge of radiative processes in the atmosphere.

It was stated previously that practically everywhere above a shallow layer next to the ground the free atmosphere suffers heat losses through the combined effects of the various radiative processes to which it is subjected. In middle latitudes at 2 or 3 kilometers above sea level, these losses would produce a cooling at fixed levels of the order of magnitude of perhaps 1° or 2° C. per day.

Thus, with the possible exception of equatorial regions, the free atmosphere everywhere serves as a cold source (condenser) for the circulation engine. Heat sources are located at the earth's surface and above the surface layers in those regions where latent heat is released through condensation. The release of latent heat through scattered, unorganized convective action is of little consequence for the atmospheric heat engine, but those regions where there is organized ascending mass motion with attending condensation and release of latent heat become important heat sources capable of driving the atmospheric circulation. It follows that the atmosphere itself to a considerable extent has the power to regulate the distribution of its heat sources and also, through dynamically produced temperature changes, to modify the intensity of its cold sources.[4] The latter effect follows from the fact that a temperature change modifies the emission, but not the absorption, of a given parcel of air.

It follows from the preceding discussion that the air ascending in the equatorial belt and spreading polewards at upper levels must lose heat fairly quickly and that parts of it must reach ground again when it is in the horse latitudes (in the neighborhood of 30° N. or S.). A branch of the descending air spreads polewards; another branch equatorwards. The poleward branch will appear as a west or southwest wind, and must eventually meet the cold air seeping equatorwards from the Pole. Forced ascent results, requiring a heat source which is provided through the release of latent heat in the ascending air.

Thus the original single meridional circulation cell characteristic of each hemisphere in the original scheme breaks up in such a fashion that one cell extends from the Equator to the horse latitudes, another from about latitude 60° polewards. The resulting scheme of circulation is illustrated in figure 4. In both extreme cells the heat sources are found at low levels, the cold sources well distributed along the vertical. Looking eastward at a meridional vertical section through the Northern Hemisphere, one would observe counterclockwise circulation in each of these extreme cells. These circulations are direct in the sense that they carry heat from heat source to cold source, all the while transforming a small fraction of the heat energy received into kinetic energy. The direct cell to the south may be called the trade-wind cell, since the southward-moving lower branch of this cell

[4] This would become significant in an atmosphere free from water vapor.

is responsible for the steady northeast trade winds just north of the Equator. For reasons which will appear, the northern cell will be referred to under the name "polar-front cell."

It now seems possible to offer an explanation also for the circulation in middle latitudes. In the two direct circulation cells to the north and to the south, strong westerly winds are continually being created at high levels. Along their boundaries with the middle cell, these strong westerly winds generate eddies with approximately vertical axes. Through the action of these eddies the momentum of the westerlies in the upper branches of the two direct cells is diffused toward middle latitudes, and the upper air in these regions is thus dragged along eastward. The westerlies observed in middle latitudes are thus frictionally driven by the surrounding direct cells. The excess of centrifugal force acting on these upper west winds of middle latitudes forces the air southward, but equilibrium is never reached, since the air still farther to the south, instead of piling up and thus permitting the establishment of an adequate cross-current pressure drop, cools through radiation and sinks to lower levels.

It has already been pointed out that the air which sinks in the horse latitudes spreads both polewards and equatorwards. The poleward branch must obviously appear as a west wind accompanied by a cross-current pressure drop northward. It continues to move northward, since the retarding influence of ground friction continually keeps the surface westerlies below the intensity required for equilibrium. Aloft the situation is reversed, since there the frictionally driven winds always remain slightly in excess of the value required to balance the cross-current pressure drop. The result is a motion northward near the surface, a slight motion southward aloft.

Thus, to an observer looking eastward, the meridional circulation in middle latitudes is clockwise and opposite to the direct counterclockwise circulations to the north and south. This middle cell serves as a necessary brake on the general circulation driven by the direct-working heat engines farther to the north and to the south. It has already

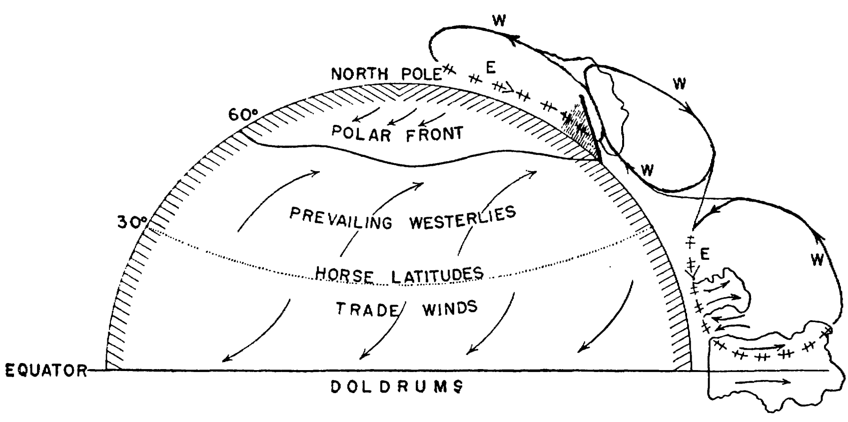

FIGURE 4.—The final cellular meridional circulation on a rotating earth: Convection near the Equator, a clear zone of descending air motion north of it (about latitude 30° N.), and heavy slanting cloud masses with accompanying precipitation in the polar-front zone (55°–60° N.).

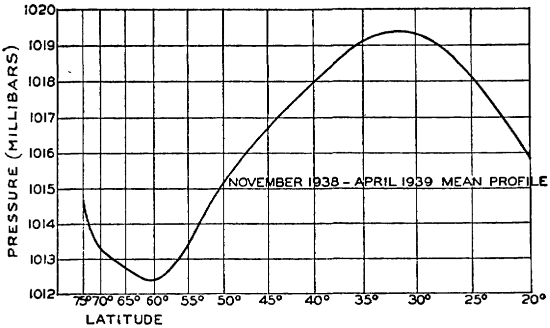

FIGURE 5.—Pressure profile for the Northern Hemisphere. (From (*2*).)[5]

been stressed that part of the (relative) momentum eastward generated aloft in the direct cells to the north and south spills over into the middle cell (through large-scale horizontal friction), where it is destroyed through slow southward displacement. The surface westerlies established in this middle cell serve the additional purpose of balancing the retarding force exerted on the earth itself by the easterlies farther south and north.

It follows from the previously established rule for the relation between wind and pressure that the sea level pressure must drop from the Pole southward to about 60° N., then rise to about 30° N., and finally drop from there on toward the Equator. At higher levels, where the wind is everywhere westerly, the pressure rises steadily from the Pole toward the Equator. Thus at sea level a trough of low pressure is established in latitude 60° and a ridge of high pressure in the vicinity of 30° N. The observed mean pressure as a function of latitude for the winter 1938–39, shown in figure 5, is in good agreement with the result of the previous analysis.

Climatic Zones

By this time it becomes possible to talk of climatic zones. The ascending motion in the equatorial region will obviously be attended by a great deal of convective activity, violent because of the extreme instability of the vertical temperature drop. Owing to the absence of horizontal contrasts, this convective activity will follow the sun with a great deal of regularity and produce the heavy afternoon showers characteristic of this climatic zone. The air descending in the horse latitudes will have lost a great deal of its moisture, and the descending motion leads to warming by compression at intermediate levels. Thus, in spite of relatively high surface temperatures, the vertical temperature drop is fairly weak and the air itself so dry as to prevent convection. This region, then, will be characterized by an arid, or semiarid, climate.

The region of ascending motion around 55° or 60° N. will obviously be characterized by a great deal of precipitation from the ascending air. It also is evident that this precipitation will be of an entirely

[5] Italic numbers in parentheses refer to Literature Cited, p. 654.

different nature from that observed in the Tropics. Because of the southward movement of cold polar air along the ground and the northward movement of warm and relatively moist subtropical air aloft, the vertical temperature drop in this region will be too weak to permit violent convection, and the precipitation must be associated with the orderly ascent of moist, warm air over the wedgelike tongues of polar air which extend southward. In this region, cold polar air and moist subtropical air converge next to the earth's surface. This, then, must be a region in which the surface isotherms, or lines of equal temperature, are constantly being crowded together and where abrupt transitions from subtropical to polar air conditions may be observed.

This transition zone, incessantly regenerated and incessantly destroyed, is in modern meteorology referred to as the polar-front zone. Here cold and warm air masses are in constant battle. This battle expresses itself through the formation of quasi-horizontal waves which normally progress from west to east along the front. The length of individual waves varies between 1,000 and 5,000 kilometers (about 600–3,000 miles). Because of the constant battle of air masses the polar-front region is characterized by strong temperature contrasts and a rapid succession of dry and wet spells.

The polar regions, characterized in the main by the descent of air which has lost most of its moisture in the ascent over the polar front, are characterized by cold arid or semiarid climate.

PLANETARY FLOW PATTERNS AND THE STABILITY OF ZONAL CIRCULATION

The preceding analysis indicates that the polar front tends to occupy a mean position parallel to a latitude circle. The Southern Hemisphere, with its practically uniform water cover, is probably to a very large extent characterized by such a zonal arrangement of the different wind belts and of the polar front. Thus it is fairly well established that the storms (polar-front waves) of high southerly latitudes move with far greater regularity from west to east than the storms of the Northern Hemisphere. This difference in behavior results from the influence of the nonzonal distribution of oceans and continents in the Northern Hemisphere, which leads to a break-down of the polar front. The break-down is reflected also in the sea-level-pressure distribution.

Figure 6 shows the practically zonal normal pressure distribution observed in the Southern Hemisphere, while figure 7 shows the extremely asymmetric normal pressure distribution characteristic of the Northern Hemisphere. Both figures refer to winter conditions. It is evident that particularly in the Northern Hemisphere the belts of high and low pressure have broken down into separate closed centers of high and low pressure. These centers are usually referred to by the somewhat misleading name "centers of action." During the winter season, at least five such centers may be observed in our hemisphere—the Icelandic and Aleutian lows, the Pacific high, the Bermuda or Azores high, and the Asiatic high. The daily synoptic weather charts for the Northern Hemisphere show a great many more moving high- and low-pressure systems, associated with the battle between cold and warm air masses along the polar front. The construction of mean charts permits the elimination of these moving

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disturbances and brings out clearly the quasi-permanent character of the centers of action listed above.

Of late such mean pressure charts for periods of a week, a month, or a season have received a great deal of attention. When a sequence of weekly mean charts is studied it is found that the centers of action may move very slowly, eastward or westward, several weeks in succession. Frequently one or several of these centers of action may break up into several parts. With the breaking up of the zonal pressure distribution into separate centers of action or cells goes a breaking up of the mean polar front into two, three, or four separate portions, usually extending from southwest to northeast. The position of these separate mean fronts is determined by the size, development, and position of the individual centers of action. Since, on the other hand, most of the storms which control weather in our latitudes move along the frontal zones thus established, it is easy to see why it is imperative to understand the factors which lead to the break-down of the ideal zonal circulation into individual centers of action. As a

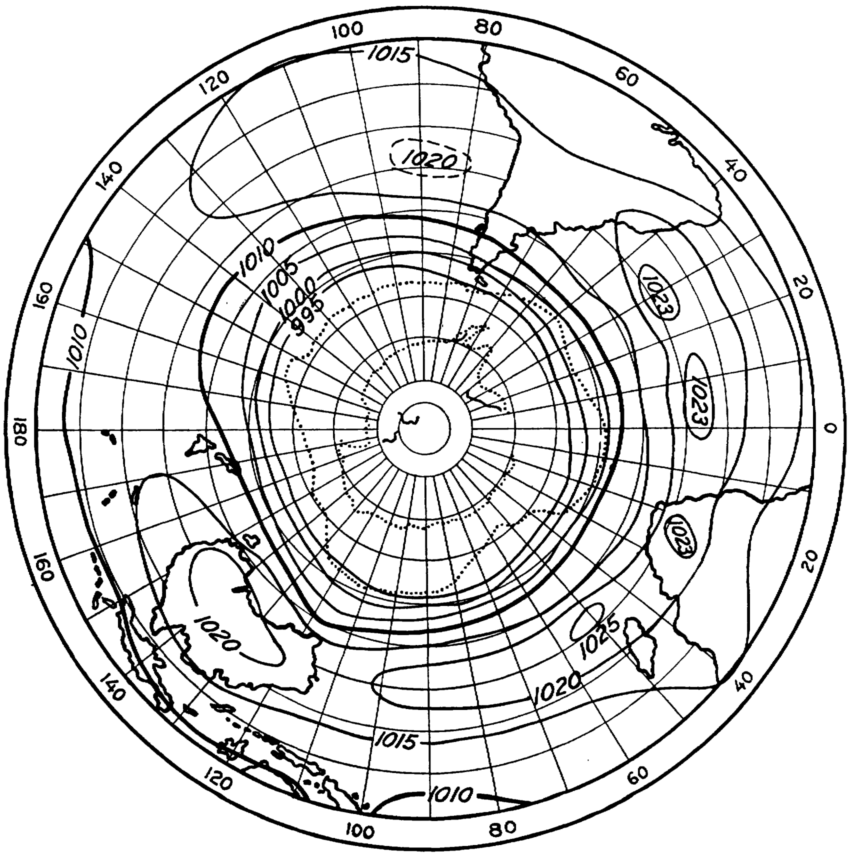

FIGURE 6.—Normal sea-level-pressure distribution (millibars) over the Southern Hemisphere in July. (From (*21*).) Compare this with figure 7 and note the great regularity and symmetry of the pressure distribution in the Southern Hemisphere, due, presumably, to the absence of large land masses.

first step it is necessary to discuss briefly the possible types of nonzonal steady flow patterns that can exist on the earth.

It is a well-known fact in mechanics that a rotating rigid body will not change its rate of rotation unless it is subjected to a force which produces a moment (torque) around the axis of rotation. If the body does not rotate initially, a torque is needed to set it in rotation. This simple principle can be applied to vertical columns of air as they move over the surface of the earth, but in so doing one must keep in mind that the earth itself is everywhere in a state of rotation around the vertical. To demonstrate this rotation it is sufficient to refer to the case of an ordinary freely suspended pendulum, which swings back and forth in a vertical plane. If a pointer is attached to the pendulum weight and permitted to trace the path of the pendulum in a sand bed just below, it will be found that the plane of the pendulum slowly turns clockwise (in the Northern Hemisphere). At the Pole the plane of oscillation would make one complete turn (360°) in 24 hours; in latitude

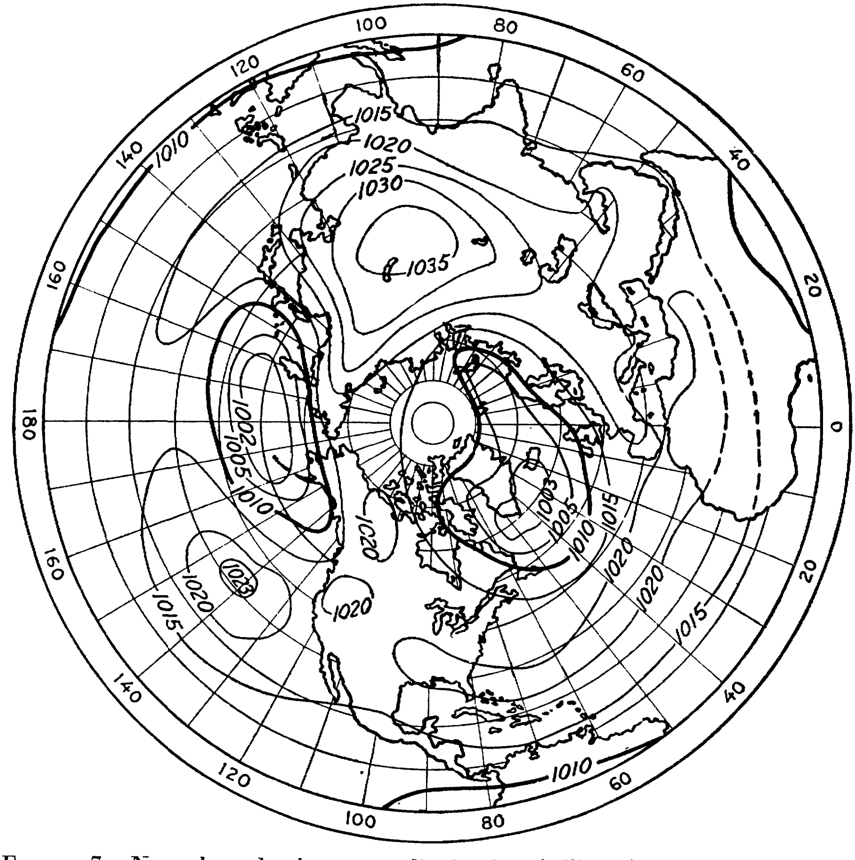

FIGURE 7.—Normal sea-level-pressure distribution (millibars) over the Northern Hemisphere in January. (From (*21*).) Note the great irregularity of the pressure distribution in the Northern Hemisphere as compared with that in the Southern (fig. 6), the two deep cyclonic (low-pressure) centers over the northernmost oceans, and the well-developed anticyclone (high pressure center) over Asia.

30° it turns more slowly, making one complete turn in 48 hours. It is well known that the time of rotation of the pendulum plane may be obtained by dividing 24 by the sine of the latitude.

It is obvious that this rotation of the plane of oscillation simply means that below our feet the earth rotates counterclockwise (clockwise in the Southern Hemisphere), rapidly at the Poles and more and more slowly as we approach the Equator. Vertical air columns which move from one latitude to another tend to take their rotation with them. Thus, a current of air originating in high northerly latitudes, where the cyclonic (counterclockwise) rotation of the earth is strong, and moving southward to a latitude where the cyclonic rotation of the earth is weak, will possess an excess cyclonic rotation around the vertical over that of the earth itself when it arrives at its destination. This excess rotation can express itself in two different ways or in a combination of both, as illustrated in figure 8.

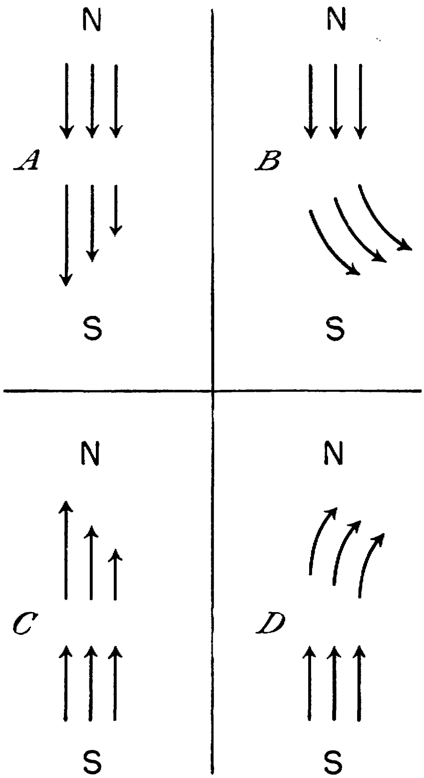

FIGURE 8.—Changes in current structure resulting from southward and northward movements in the Northern Hemisphere: *A*, A narrow current moving southward would, if forced to follow a straight path, acquire a strong cyclonic (counterclockwise) shear; *B*, if free to seek its own path, it would curve around cyclonically; *C*, a narrow current moving northward would, if forced to follow a straight path, acquire a strong anticyclonic (clockwise) shear; *D*, if free to seek its own path, it would curve around anticyclonically. In all cases the current would pile up air on the right-hand side looking downstream, but the slight deflections needed to bring this about would not materially affect the flow patterns illustrated.

The current can follow a straight path but develop a shear so that the right edge of the current (looking downstream) moves faster than the left edge (fig. 8, *A*). In the atmosphere there are several influences at work that normally prevent the development of strong shear zones and lead to the establishment of currents of fairly uniform velocity cross-stream. In that case the current is forced to bend around cyclonically, as indicated in figure 8, *B*. Figures 8, *C*, and 8, *D*, illustrate the corresponding effects in a north-bound current developing anticyclonic (clockwise) rotation.

When the mean zonal circulation was discussed, a uniform seeping southward of cold air from high latitudes was assumed. In that case there is, of course, no possibility for the establishment of cyclonically curved stream lines, and the excess of cyclonic rotation in the southward-moving belt of cold air should therefore lead to strong cyclonic shear in the northern belt of easterlies. Likewise, in the free atmosphere, where rings of air are displaced northward toward regions where the earth itself rotates more rapidly counterclockwise (cyclonically) around the vertical, the resulting deficiency in rotation of the displaced air columns must express itself in the form of anticyclonic shear. However, in both cases it can be said that the statistical mean northward and southward velocities associated with the general circulation between latitudes are so weak that frictional forces of all kinds have ample time to prevent the establishment of sharp shear zones. The situation is different in the case of air currents that for some reason or other are definitely deflected from their east-west motion. In these currents latitude changes occur so quickly that the frictional forces have inadequate time to act. In such currents, the excesses or deficiencies in rotation have a tendency to produce curved flow patterns. Initially straight currents from the north curve around cyclonically, currents from the south curve around anticyclonically.

It is particularly interesting to apply these results to a study of the stability of west-wind or east-wind belts of limited width. If a current from the west at some point in its path is subjected to a cyclonic torque which gives it a slight deflection northward, it follows that the current from then on will head toward higher latitudes, where the rotation of the earth itself around a vertical becomes stronger and stronger. Thus the relative cyclonic rotation (curvature) which the current acquired at the initial point of deflection will decrease and eventually, after sufficient displacement northward, change into an anticyclonic curvature. The current will then finally bend back toward its equilibrium position. As it moves southward it will pick up cyclonic relative rotation (curvature), and the net effect will be a sinusoidal, or wavelike, oscillation of the west-wind belt around a certain mean latitude, such that the current will form a series of standing waves downstream from the point at which it was disturbed initially.

The amplitude of these waves depends upon the intensity of the initial disturbance, but the wave length depends principally on the strength of the west-wind belt. The stronger the wind, the longer the wave length. For the wind velocities prevailing in the upper troposphere in our middle latitudes in wintertime, this wave length is of the order of magnitude of 5,000 kilometers (3,000 miles). These

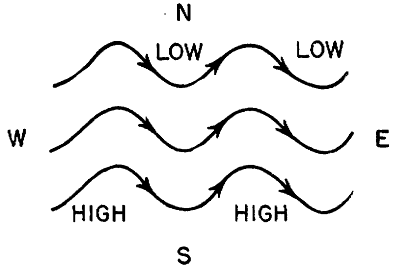

FIGURE 9.—Diagram of waves on a broad west-wind belt, showing troughs of low pressure and ridges of high pressure.

"resonance" waves give us a length scale for the large semipermanent centers of action into which the previously described symmetric zonal circulation actually breaks up.

If the same type of reasoning is now applied to a narrow current from the east, which at a given point in its path is given a slight cyclonic rotation (cyclonic curvature), it follows that the current from then on moves slightly southward. However, the farther south it moves, the stronger will be the cylonic rotation of the current, since it is constantly moving toward latitudes where the earth's own cylonic rotation around the vertical becomes weaker and weaker. Thus the current is deflected farther and farther away from its equilibrium latitude. Finally it will have turned around completely and will then appear as a west wind, but with sufficiently strong cylonic curvature to return to its original path. If the current had originally been deflected northward it would describe a complete anticyclonic circuit. This may be of importance in connection with the breaking up of the high-pressure belt around latitude 30°. It is fairly evident that the cold easterly winds to the north, because of the large body of cold air over the Arctic, are constrained to break up into cyclonic vortices.

The analysis shows that easterly winds are unstable and tend to break up into large cyclonic or anticyclonic eddies. The dimensions of the eddies thus formed increase with the velocity of the east wind itself, and they agree reasonably well with the dimensions of the cy-

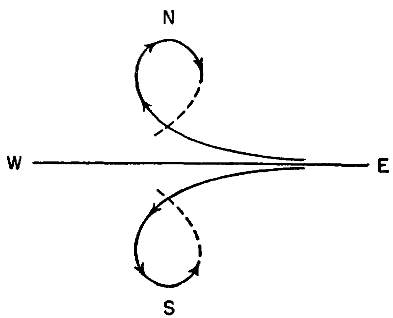

FIGURE 10.—The upper curve represents the path of a narrow east-wind belt which has received a small initial deflection northward. The lower curve represents the path of a current which has received an initial deflection southward. Since a current in a state of steady motion cannot intersect itself, the analysis suggests that narrow east-wind belts are unstable, resulting in the intermittent formation of large vortices.

clonic centers of action referred to above. Figure 9 illustrates a steady resonance wave on a broad west-wind belt and figure 10 the trajectory of a deflected east-wind belt of narrow width.

To completely understand the behavior of cold currents from the north a further reference should be made to the spinning-marble experiment discussed earlier. It was pointed out that by a shortening of the string the marble could be made to spin faster and by a lengthening of the string to spin more slowly. In the same way, the outer edge, or periphery, of a rotating column of air which is stretched vertically and shrunk horizontally will spin around more rapidly; if the column shrinks vertically and stretches horizontally it will spin more slowly. In applying this result to vertical columns in the atmosphere it is necessary to consider the absolute rotation. It thus follows that air columns which stretch vertically must acquire an excess (cyclonic) rotation relative to the earth, while air columns which shrink vertically acquire a deficient (anticyclonic) rotation relative to the surface of the earth.

It is a well-established fact that cold currents from the north gradually sink and spread out next to the surface of the earth. This sinking is most marked along the right-hand edge of the cold current (for an observer facing downstream). Thus the left-hand branch of the current curves around cyclonically as a result of the decrease in latitude, but the right-hand branch, in which strong sinking occurs, curves around anticyclonically. As a result the deflected cold current spreads south in a fanlike fashion.

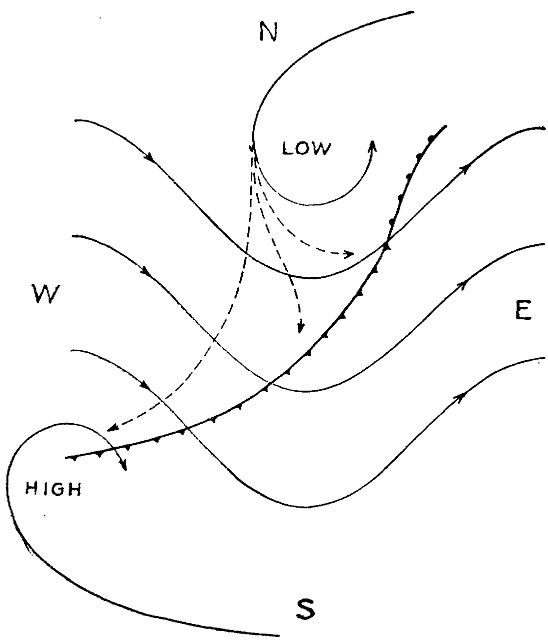

FIGURE 11.—Break-down of the zonal polar front and establishment of a typical branch front through the injection of polar air into a trough in the westerlies. Subsiding, undercutting branches of the polar air take on anticyclonic curvature (broken lines); nonsubsiding branches will curve around cyclonically and form the left edge of the cold wave. The polar front is indicated by a barbed line.

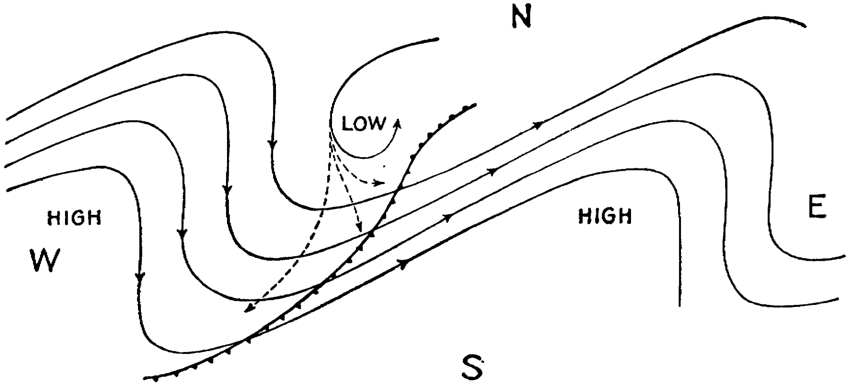

FIGURE 12.—Injection of polar air into a slanting trough of the westerlies. Such troughs may easily form as a result of thermal perturbations of the westerlies set up along the slanting eastern coast lines of Asia and North America-Greenland.

If for some reason the westerlies of middle latitudes are disturbed and a quasi-stationary wave pattern is established, the pressure will drop wherever a wave trough is being established. Cold air from the north will be pulled into these low-pressure troughs. Hence intermittent outbreaks of cold polar air from the previously undisturbed east-wind belt to the north are likely to occur wherever there is a trough toward the south in the westerlies. Corresponding outbreaks of warm and moist air from the southern belt of easterlies tend to occur where the westerlies are deflected northward. One obtains in this way the pattern of flow illustrated in figure 11, which in several respects well describes the observed flow pattern in the atmosphere. It is obvious that this pattern leads to a breaking up of the polar front into separate portions which run roughly from southwest to northeast. Along these individual polar fronts, waves form which move northeastward and gradually die out in the central low-pressure areas to the north.

Figure 12 represents a modification of figure 11 obtained by assuming that the crests and valleys of the quasi-permanent waves in the west-wind zone extend from southwest to northeast, parallel to three of the four principal boundaries between oceans and continents in the Northern Hemisphere. This theoretical picture agrees remarkably well with the observed mean pressure and frontal distribution in any one of the principal frontal zones of the Northern Hemisphere.

To each speed of the westerlies corresponds one definite resonance wave length, and this wave length increases with increasing strength of the westerlies. Thus it appears that the number of points where polar air is simultaneously injected into the west-wind zone depends upon the strength of the westerlies and decreases as the westerlies increase. In the Southern Hemisphere, where land masses are relatively insignificant or, in the case of the Antarctic Continent, symmetrically distributed, these injection points may occur in any longitude and thus the mean wind and pressure distributions should appear fairly uniform around the globe. In the Northern Hemisphere, on the other hand, preferential injection points are established, and the final mean pressure distribution is thus far from symmetric around the axis of the earth.

INTENSITY FLUCTUATIONS IN ZONAL CIRCULATION AND THE CIRCULATION INDEX

In view of the fact that the dimensions and positions of the circulation patterns associated with strong and weak circulation differ in a characteristic fashion, it is evidently important to develop a simple index to the intensity of the zonal circulation. It has been pointed out previously that the surface westerlies in middle latitudes form a part of a reverse meridional circulation cell which is driven by the direct cells to the north (polar-front cell) and to the south (trade-wind cell). Because of this frictional drive it is reasonable to assume that these surface west winds, at least qualitatively, furnish a good measure for the variations in the general zonal circulation of the atmosphere. A simple measure of the intensity of these sea level westerly winds may be obtained by taking the difference between the mean pressure observed in latitude 35° N., near the center of the subtropical high, and the mean pressure observed in latitude 55° N., just south of the pressure trough normally prevailing in the vicinity of latitude 60° N. This mean-pressure difference is very nearly proportional to the mean wind component from the west prevailing within this zone, if surface frictional forces are disregarded. In view of the variations in the difference between the mean temperature of an air column in latitude 35° N. and another air column in latitude 55° N., it is, unfortunately, impossible to use the same mean-pressure difference as a quantitative measure of the mean west-wind component at higher levels within the same zone, but it should at least serve as a qualitative index to the variations in circulation intensity at higher levels.

Mean weekly values of this circulation index have been computed since 1936 and show amazingly strong fluctuations from week to week in the circulation intensity. During the winter season these fluctuations range from an index value of about 15 millibars to one of about −5 millibars, the latter value indicating an actual reversal of flow in the surface layers (east wind). These fluctuations are well illustrated by the curve in figure 13. The variations in circulation intensity are obviously fairly irregular, but it is also evident that trends persisting through 3 or 4 weeks are fairly common during the winter. The irregularity of the variations in circulation intensity is sufficiently pronounced to effectively eliminate all possibility of long-range forecasting on the basis of periodicities, but the persistence tendency in the index curve is sufficiently high to permit judicious extension (extrapolation) of a trend for a week at a time. During the summer the fluctuations in circulation intensity are somewhat smaller and also more irregular. It is hard to see how adequate short-term long-range weather forecasts can be developed until there is an adequate understanding of these amazing fluctuations in the zonal circulation intensity.

It has already been mentioned that the energy of the westerlies depends upon the meridional circulation between heat sources and cold sources in the two direct meridional cells, to the north and to the south of the westerlies. It would, therefore, seem probable that a

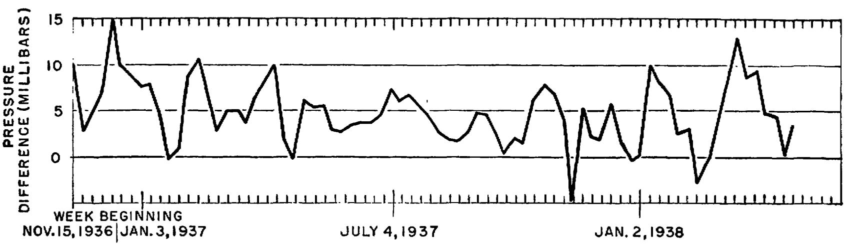

FIGURE 13.—Zonal circulation variations during the period November 1936–May 1938. (Adapted from (2).) This index to the zonal circulation is computed weekly as the difference between the mean pressure at latitude 35° and the mean pressure at latitude 55°. The greater this index is, the stronger the prevailing west wind in middle latitudes. Note the large amplitude of fluctuations in winter, particularly the occurrence of long trends downward or upward through several weeks in succession.

satisfactory understanding of the variations in the zonal circulation intensity cannot be reached until fairly complete temperature and humidity data from the upper atmosphere over the entire Northern Hemisphere are available in the form of daily routine measurements. No adequate physical theory is available at the present time from which the fluctuations in circulation intensity may be computed, but recent studies suggest that these fluctuations may be associated with the intermittent establishment of a direct inflow of deep, moist air from the equatorial trade-wind belt into the westerlies of middle latitudes. There is good reason to hope that the problem of the circulation fluctuations will be brought much closer to its solution within the next few years.

INFLUENCE OF LAND MASSES AND OCEANS ON THE CIRCULATION PATTERN

In older writings it is sometimes stated that the difference between land climate and sea climate is caused by the difference in specific heat between water and solid rock. It is more correct to emphasize that the upper layers of the ocean are nearly always in a state of violent stirring whereby heat losses or heat gains occurring at the sea surface are distributed throughout large volumes of water. This mixing process sharply reduces the temperature contrasts between day and night and between winter and summer.

In the ground, there is no turbulent redistribution of heat, and the effect of molecular heat conduction is very slight. Thus violent contrasts between seasons and between day and night are created in the interior of continents. During the winter the snow cover which extends over large portions of the northern continents reflects back toward space a large part of the sparse incident solar radiation. For these various reasons the northern continents serve as efficient manufacturing plants for dry polar air. The polar air cap is no longer symmetric but is displaced far to the south, particularly over the interior of Asia. This in turn means that the mean polar-front zone is deformed and tends to follow the boundaries of the northern continents, extending northeastward along the Pacific coast of Asia, then southeastward along the Rockies, and finally northeastward along our Atlantic coast toward Iceland. Our knowledge of the upper westerlies at high levels is still very incomplete, but it appears that they, too, are displaced southward over the Asiatic Continent.

The polar air which is being steadily manufactured over the interior of Asia generates a polar front which in the main follows the Pacific coast line of that continent. Just as pure easterly winds are established behind the mean polar front on a symmetric globe, northeasterly winds will be established to the north and west of the Asiatic polar front and southwesterly winds south and east of the same front. This arrangement of currents is, however, highly unstable. It has already been brought out that currents from the north tend to assume cyclonic curvature unless they have an opportunity to sink and spread out. The cold currents from the north behind the Asiatic polar front cannot spread out toward the interior where still deeper masses of cold air are stored. Hence they must stream south over the Pacific, and these intermittent outbursts help to maintain a deep cyclonic vortex off the Pacific coast of Asia.

The air masses which are found south and east of the Asiatic frontal zone and at higher levels stream toward the Aleutian Islands. As they move northward they must gradually curve around anticyclonically (clockwise). It has already been pointed out that the wave length of such an oscillating west-wind belt increases with increasing wind velocity. Hence, if the southwest or west-southwest winds off the coast of Asia are sufficiently strong they will follow the boundaries of the north Pacific Ocean, curving around anticyclonically as a result of their northward displacement. In this case a single frontal zone is established, along which storms move rapidly in an eastward direction, crossing the Pacific coast of North America in fairly high latitudes (British Columbia, Washington, Oregon).

On the other hand, as the southwesterly winds off the coast of China grow weaker, they tend to curve around anticyclonically much more sharply. A trough of low pressure may then be created in the middle or eastern part of the Pacific, and thus another injection point for polar air may be established. A new polar front, extending across the mid-Pacific from southwest to northeast, may thus be established by purely dynamic means, whenever the general circulation slows down. Storms (waves) traveling northeastward along this polar front bring moist, southerly winds to California. These moist air masses are trapped between the Pacific polar front on the one hand and the mountains and the cold air masses over the continent on the other. They are therefore forced to ascend, and in so doing they probably produce a large portion of the winter rains in southern and central California.

As a result of the production of polar air over Greenland and the North American continent, another polar-front zone is established over the Eastern States, extending from the lower Mississippi Valley over New England, Newfoundland, and the northern North Atlantic toward northern Norway. When the circulation in middle latitudes is very weak, a second Atlantic polar front may be established over western Europe. This doubling of the Atlantic polar front appears to be a more infrequent phenomenon than the doubling of the Pacific polar front.

Figures 14 and 15 represent an attempt at a comparison of the observed pressure distribution during a period of very weak zonal movement in middle latitudes with the computed air trajectories during a period of weak circulation. The observed pressure distribution (fig. 14) shows that the Aleutian low has split into two separate centers, one off Kamchatka and one in the Gulf of Alaska. Likewise, the Icelandic low has split up, with one center over Labrador and a second center in the form of a long trough extending southwestward from Spitzbergen to a point off Ireland. The center positions of these observed cyclonic whirls agree fairly well with the computed circulation centers in figure 15.

In computing this last circulation diagram it was assumed that the easterlies to the north have a mean velocity of 8.9 meters per second, the westerlies in middle latitudes a mean velocity of 15.5 meters per second, and the easterlies still farther to the south a mean velocity of about 13.3 meters per second. These velocities were chosen so as to give a proper wave length for the westerlies and the proper dimensions for the cyclonic and anticyclonic eddies to the north and

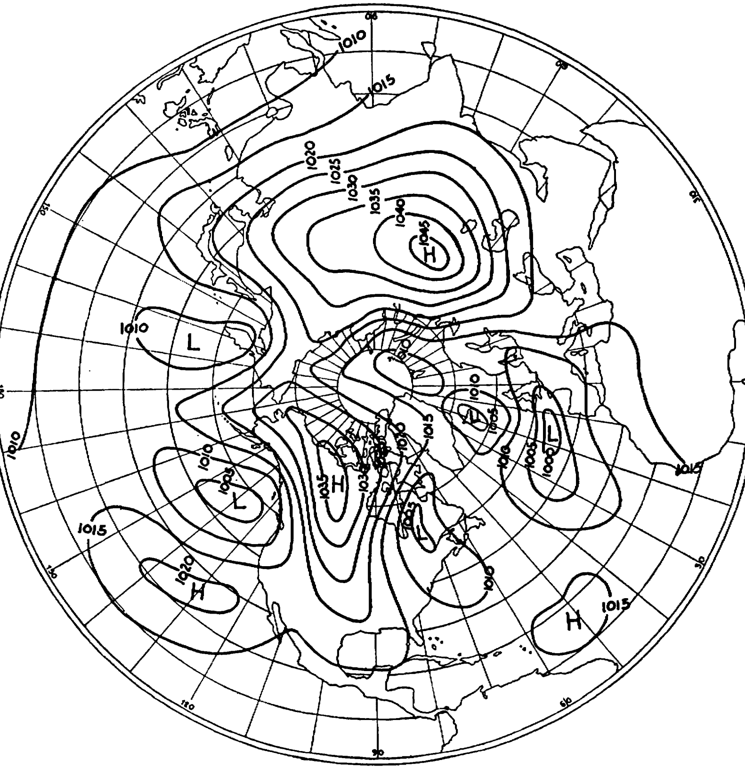

FIGURE 14.—Mean sea-level-pressure distribution (millibars) during a week of slow zonal circulation, November 14–20, 1937. (From (2).) Note two separate low-pressure centers in the Pacific, a well-developed continental high in North America, the split character of the Icelandic low, and the displacement toward Europe of the Asiatic high.

south. Thus the only claim that can be made for this theoretical analysis is that with reasonable values for the prevailing zonal winds it leads to flow patterns of a high degree of verisimilitude. In view of the disturbing influence on the mean zonal pressure distribution of the relatively shallow, cold anticyclones over Asia and North America, it is impossible to start the analysis from the observed zonal pressure distribution.

It is fairly apparent that both the theoretical and the observed circulation imply the existence of double polar fronts both in the Pacific and in the Atlantic. The positions of these mean fronts have been indicated by broken lines in figure 15.

During periods of strong circulation the theoretical resonance wave length analyzed previously becomes too large for the development of two frontal zones either in the Pacific or in the Atlantic. The resonance wave pattern is no longer free to develop, and the circulation pattern is probably mainly a function of the distribution of continents and oceans.

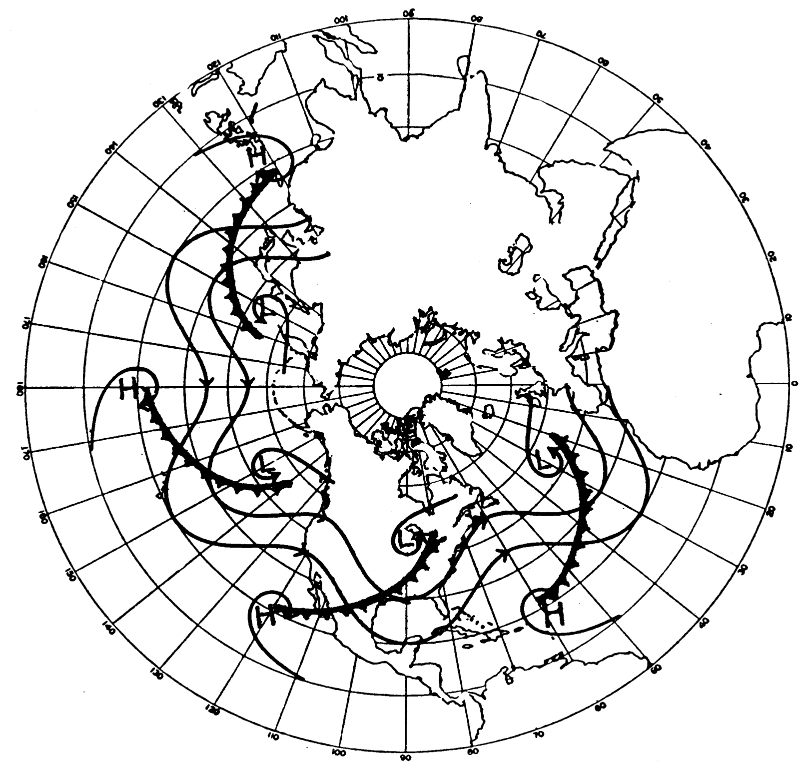

FIGURE 15.—An example of the theoretical planetary flow pattern for weak zonal circulation. Compare this diagram with figure 14 and note the presence in both of a split Aleutian low and a split Icelandic low, with one branch centered over eastern North America. In comparing the two diagrams it should be remembered that the wave pattern of the westerlies indicated here is in reality (fig. 14) obscured by shallow cold-air anticyclones but that it would appear clearly on a corresponding chart for the 3-kilometer level.

Figure 16 is typical of the mean pressure distribution during periods of strong circulation. A comparison between figures 14 and 16 reveals certain marked contrasts which appear to be typical.

During periods of strong circulation both the Aleutian and the Icelandic lows are characterized by single, well-developed centers and by large dimensions. The Aleutian low is then normally located near the Alaskan Peninsula and the Icelandic low in the vicinity of Iceland or even east and north of it.

During periods of weak circulation one or the other or even both of these centers split into two separate cells of smaller dimensions than normal. One part of the Aleutian low may be found near Kamchatka; one in the Gulf of Alaska. At the same time the Icelandic low is frequently displaced westward and southward, or it may, as in figure 14, split into two cells.

During periods of strong circulation, a fairly well developed high-pressure area, often referred to as the Great Basin high, is usually found over the southern portion of the Rocky Mountain States. This is really a part of the subtropical (warm) high-pressure area. North of this high-pressure area there is a rapid inflow of relatively mild

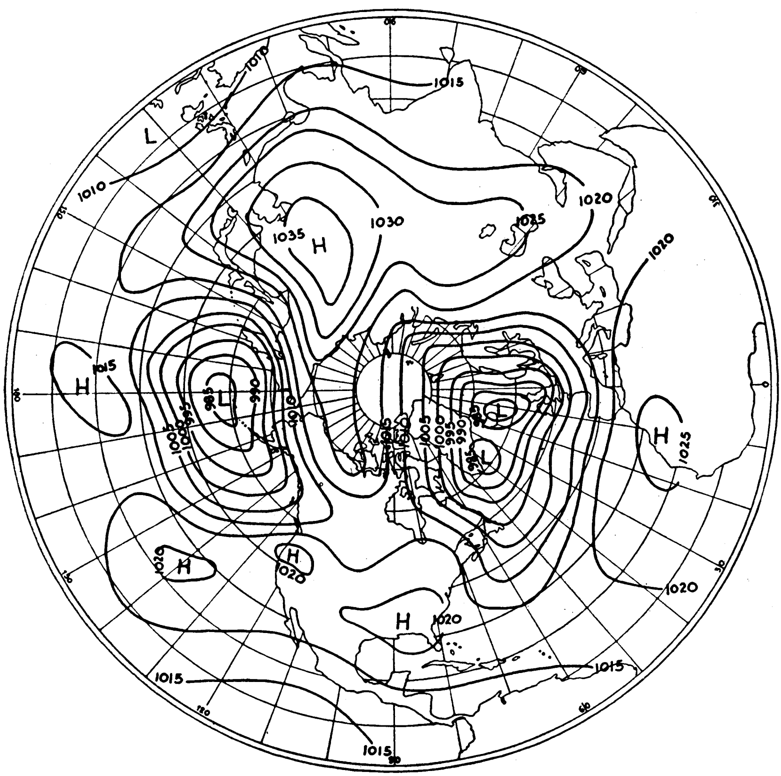

FIGURE 16.—Mean sea-level-pressure distribution (millibars) during a week of strong zonal circulation (January 9–15, 1938). (From (*2*).) Note the presence of a single strong Aleutian low, a single Icelandic low, and the displacement toward the Pacific of the Asiatic high.

Pacific air masses over the United States, and rapid air motion eastward prevails over the Northern States. There are very few indications of the development of a cold continental anticyclone over the interior of this continent.

During such periods of strong circulation, maritime inflow from the southwest characterizes weather conditions in northwestern Europe. Both our Pacific Northwest and northwestern Europe are then dominated by a rapid succession of wave cyclones—warm, moist, subtropical air masses alternating with relatively mild, maritime polar air masses moving in from the west or northwest. Rainfall on the Pacific coast occurs mainly far to the north, in British Columbia or Washington and Oregon.

Finally, during such periods of strong circulation, the Asiatic high appears to be displaced toward the Pacific side of Eurasia.

On the other hand, as the zonal circulation of middle latitudes weakens and finally reaches a minimum value, there is a marked tendency for the Great Basin anticyclone to disappear and for a strong continental anticyclone to develop over the interior of North America. The center of this anticyclone is located far to the north, in Canada, and a wedge of high pressure extends southward into the United States. Thus, in the surface layers, there is very little air movement from west to east across North America. At the same time, the Asiatic anticyclone is usually displaced westward, toward Europe. The effects of these pressure changes on weather conditions are profound. There will now be an outflow of cold continental air from the east over Alaska and even over British Columbia, and another outflow from the southeast of extremely cold continental air from Asia over northwestern Europe.

The polar-front cyclones, which move up over the Pacific toward that portion of the Aleutian low which during periods of weak circulation is located in the Gulf of Alaska, are quite apt to bring with them warm, moist air masses from the southwest. It has already been brought out that these moist currents are frequently trapped between the polar air masses which come down over the Pacific to the west and the mountains and continental air masses to the east. Thus forced to ascend, the moist air yields heavy rainfall fairly far south on the Pacific coast.

During periods of weak circulation, the theoretical sea-level-pressure distribution is so disturbed through the development of continental anticyclones that it may become unrecognizable. For this reason it is of some interest to look at the pressure distribution at higher levels, say 3 kilometers (about 2 miles), as determined with the aid of upper-air data now available daily from a number of stations in the United States (figs. 17 and 18). In figure 18, corresponding to a period of weak circulation, there are good indications of low-pressure troughs off the Pacific coast and east of the Atlantic coast. Figure 17, corresponding to a case of strong circulation, shows a single well-marked trough, probably an extension of the Icelandic low, extending southwestward through the Mississippi Valley.

During periods of strong circulation, characterized by strong west-to-east movements in middle latitudes, the belt of westerlies is usually displaced somewhat to the north of its normal position. Because of the prevailing strong winds, intense lateral mixing and turbulence

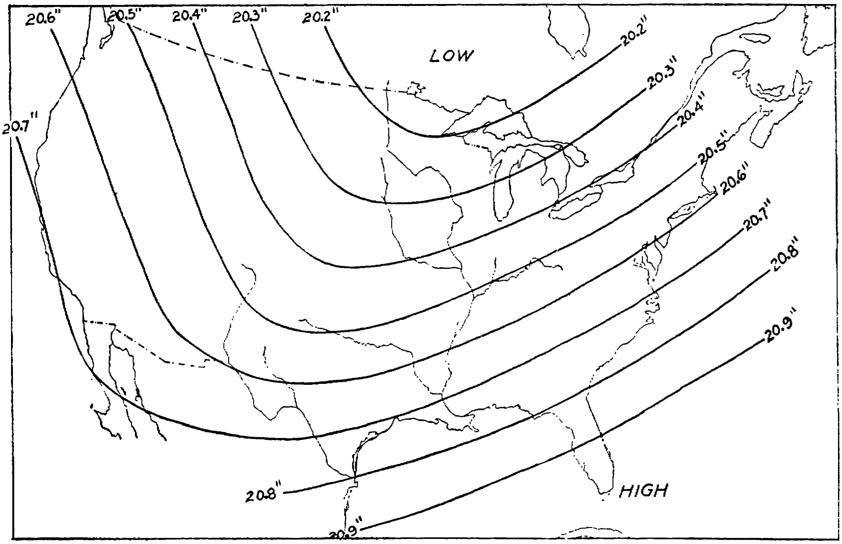

FIGURE 17.—Mean pressure (inches) at the 3-kilometer level for the 5-day period February 26–March 2, 1939. This map corresponds to a period of strong circulation. (From (2).) Notice the general trend of the isobars from west-southwest to east-northeast in the eastern half of the country, indicating a general west-southwestern wind. This type of wind distribution aloft in the eastern part of the United States corresponds to temperatures well above normal.

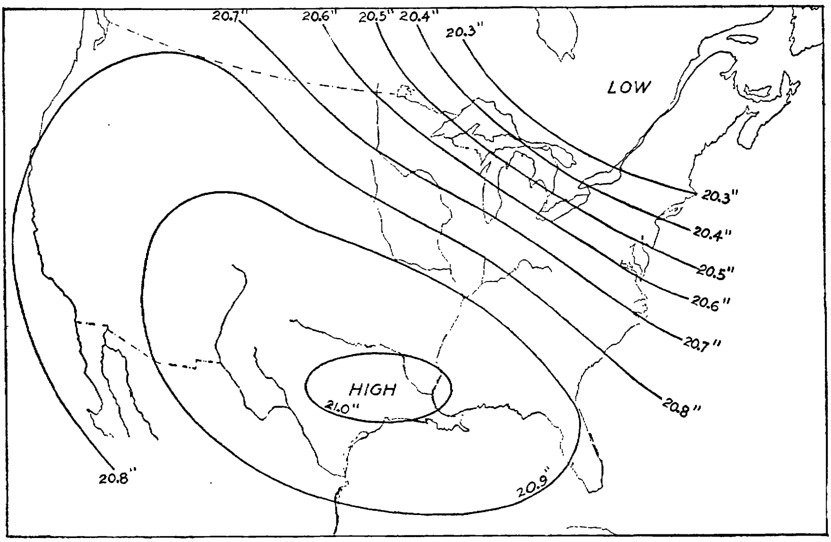

FIGURE 18.—Mean pressure (inches) at the 3-kilometer level for the 5-day period March 19–23, 1939. This map corresponds to a period of weak circulation. (From (2).) Notice the west-northwest winds over the Middle West and the East, corresponding to temperatures well below normal in these sections. This pressure distribution suggests two troughs, one over the Atlantic coast and another over the Pacific just off the California coast.

develop in middle latitudes. This mixing process transports heat northward and creates positive temperature anomalies in middle latitudes and presumably negative ones farther south. During periods of weak circulation, the west-east components decrease in intensity, and there is a pronounced tendency toward the development of large-scale north-south current systems. At such times regions of positive and negative temperature anomalies will appear side by side, but their position will not always be the same, as may be inferred from the previous discussion of the relation between the size of the stationary flow patterns and the prevailing zonal-circulation intensity. The four anomaly charts, figures 19–22, are intended to bring out these differences between periods of strong and weak circulation.

The value of the relationship described above between the observed circulation pattern and the intensity of the zonal circulation lies in the fact that it reduces the number of variables to be considered in any discussion of weather types by establishing two idealized world pressure patterns, for periods of maximum and minimum circulation intensity. Given the values of the zonal circulation index during a few consecutive weeks (during the winter season) it is probably possible, from these values alone, to give a description of the mean pressure distribution at the end of the period that will be decidedly better than a pure guess, although definitely subject to a considerable margin of uncertainty. Until it becomes possible to predict the fluctuations in the zonal-circulation index, it is of course impossible to utilize this knowledge with full effectiveness in forecasting.

The preceding discussion suggests another important application.

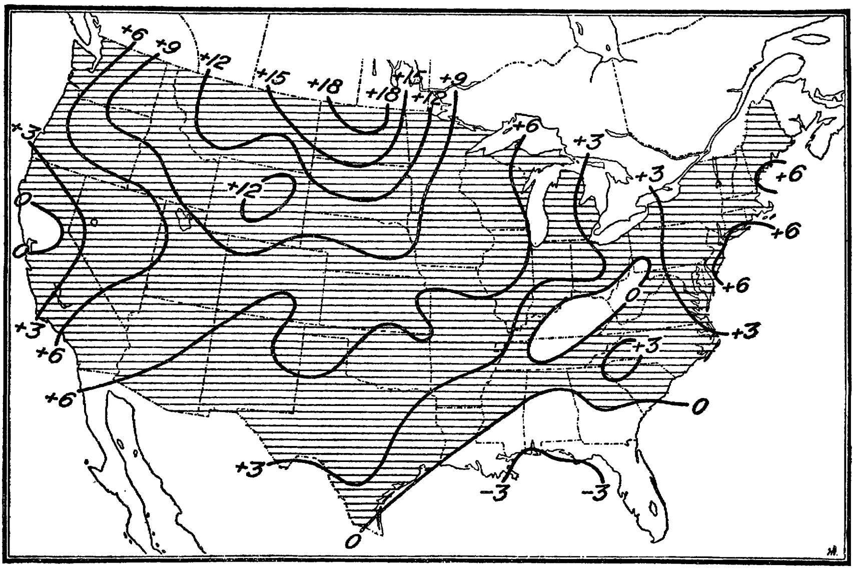

Figure 19.—Temperature departure from normal, in ° F., for a period of maximum circulation. The index at this time was 13.2 millibars. (From (2).)

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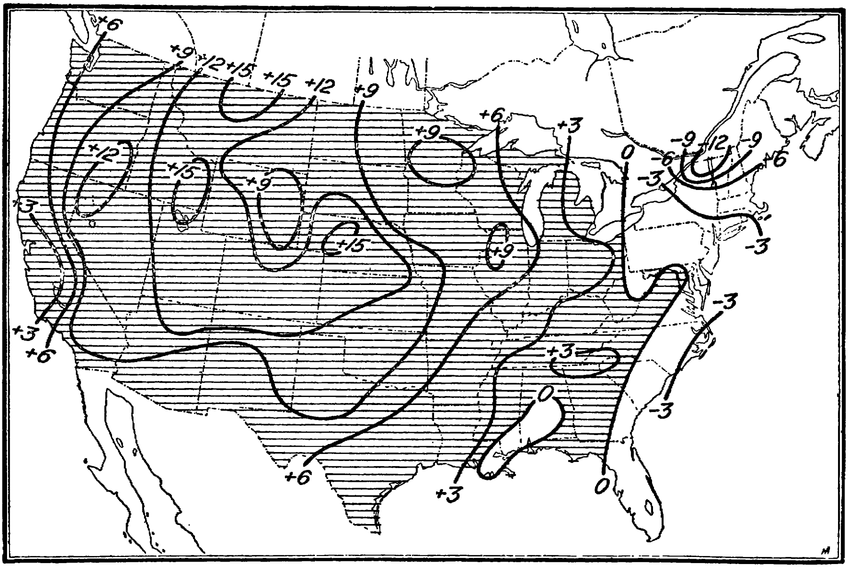

FIGURE 20.—Temperature departure from normal, in ° F., for a period of maximum circulation. The index at this time was 12.5 millibars. (From (2).)

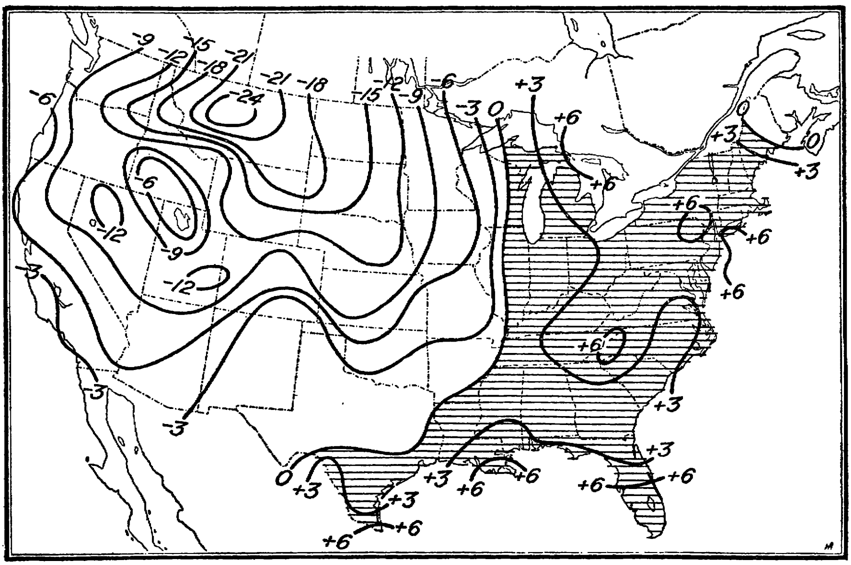

FIGURE 21.—Temperature departure from normal, in ° F., for a period of minimum circulation. The index at this time was —1.4 millibars. (From (2).)

It should be possible to establish relationships corresponding to (but not necessarily identical with) the ones described above, between mean zonal-index values and mean circulation patterns for longer periods (months or years). The establishment of such climatic patterns, having a physical background, should be of great value in

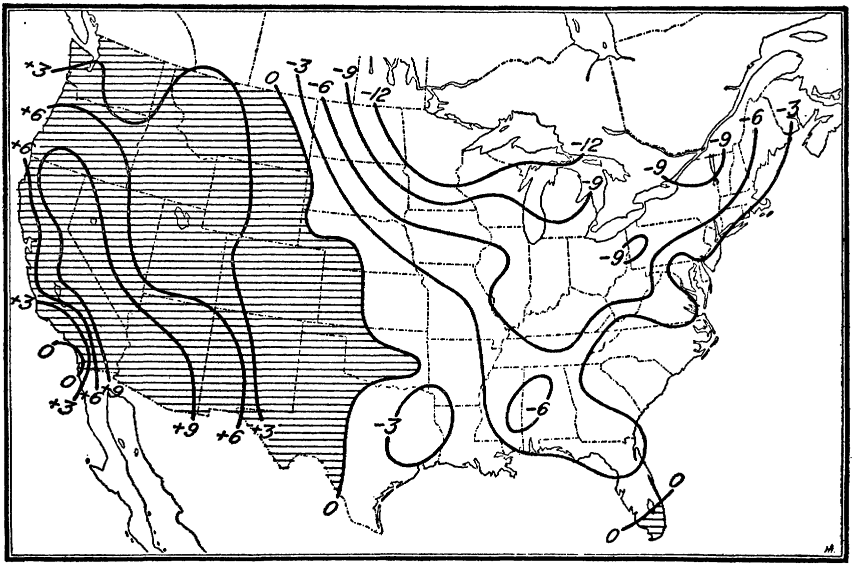

FIGURE 22.—Temperature departure from normal, in ° F., for a period of minimum circulation. The index at this time was 0 millibars. (From (2).)

the analysis of past climatic fluctuations and should serve to emphasize the need for restraint in this field of research, by bringing out the self-evident fact that the sequence of past climatic events can vary only very slightly from point to point. Hence, the geographic distribution of the climates assumed to have prevailed during a certain geological period must follow a pattern which is compatible with accepted physical and meteorological principles.

POLAR-FRONT WAVES

It has been brought out that the polar front must break down into several disconnected parts extending normally in a southwest-northeast direction. Under steady conditions each such front would represent the intersection with the ground of a sloping boundary surface, ascending toward the northwest and separating a wedge of polar air moving southwestward from a warm and moist current moving northeastward above and to the southeast of the front. Actually this front is never in stable equilibrium, but along it waves will develop which normally move northeastward while at the same time often increasing in horizontal and vertical amplitude. It is the interaction of cold and warm air masses in these waves that is responsible for the storms which control the day-by-day changes in weather so characteristic of our latitudes.

An idealized picture of such a wave is given in figure 23. The center portion of this diagram gives a horizontal projection of the wave, as observed at the ground. The polar front itself, indicated by a broken line, extends northward into the domain of the cold air. The instantaneous direction of motion of the warm air is indicated by the arrows on the double lines, while the direction of motion of the cold air is indicated by heavily drawn single lines.

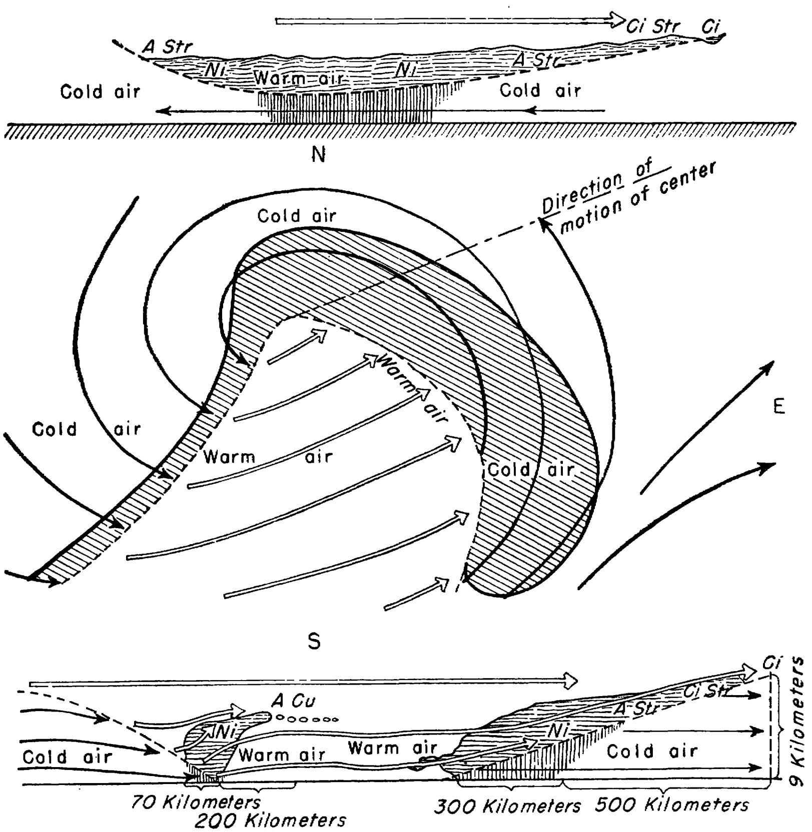

FIGURE 23.—Idealized polar-front wave. (From Haynes (*10*).) In the center is a horizontal view of the distribution of air masses at the ground. The broken line is the boundary (polar front) at the ground between a warm current from the west-southwest (white arrows), displacing to the east a wedge of cold air (black arrows) returning northward from a brief sojourn in southern latitudes. Along the boundary of the receding cold air (warm front) the warm air rises, and its moisture condenses and produces a broad area of rain or snow (shaded area). The upper part of the diagram represents a vertical west-east section north of the center, the lower part a similar section south of the center. (A Str means alto-stratus clouds; Ni, nimbus; Ci Str, cirro-stratus; Ci, cirrus; A Cu, alto-cumulus. Figures in the lower diagram are approximate.)

Along its advancing edge the warm air is forced to rise over the cold air. Because of the resulting expansion under decreased pressure, the warm air cools, condensation results, and rain must fall within the hatched area indicated in the diagram. In the rear of the warm current, cold air advances from the northwest; the sinking cold air moves more rapidly than the retreating warm air and forces the latter upward, again producing condensation and precipitation.

That portion of the polar front along which warm air replaces cold is referred to as a warm front, while the portion along which cold air replaces warm is called a cold front. Because of frictional retardation along the ground, the shallow wedge of cold air ahead of the warm front moves fairly slowly. At the cold front, cold surface air is retarded by friction, but the upper layers are free to move at high speed, so that the cold front may advance rapidly through the development of a rolling or overturning motion within the cold air. Thus the cold front normally moves faster than the warm front and eventually overtakes it.

Above and below the horizontal view in figure 23 are two idealized vertical sections of a polar-front wave, one (above) extending from west to east, north of the wave center, and the other (below) from west to east south of the wave center. These sections give a good

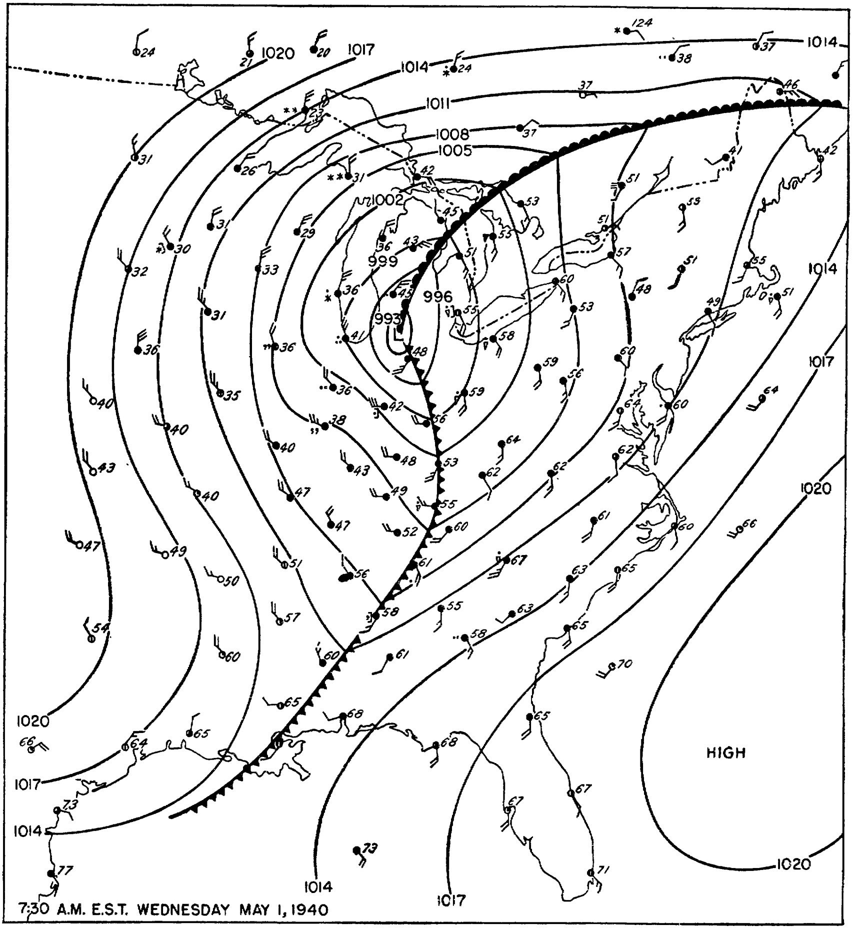

FIGURE 24.—An example of a polar-front wave over the United States. (From (*10*).) The cold front is indicated by the barbed line, the warm front by the line with filled half circles. The eastern part of the country is located within the warm air, and the western part and the upper Great Lakes region are in the cold air. This may be seen from the temperatures (in °F.) at each station. The wind direction is shown by arrows, attached to the circles representing the stations, which point in the direction toward which the wind is blowing, and wind velocity is indicated by cross bars on the arrows, one full bar denoting approximately 5 miles per hour. The degree of cloudiness is indicated by the extent to which the station ring is filled. Note the counterclockwise wind circulation around the low-pressure center east of Lake Michigan.

indication of the typical cloud decks that develop along the boundary between the two air masses in such a polar-front wave.

The ascent of warm air at the warm front is usually steady, and the rainfall has the character of steady rain. If the warm air is unstable, however, this instability may be released through forced ascent, and the steady warm-front rain may then be intensified in spots into violent convective rain. This occurs fairly frequently in the warm-front rains in the southern part of the United States but it is quite uncommon in northwestern Europe.

At the cold front the forced ascent of the warm, moist air is much more violent and intermittent; it is accompanied by squally winds, and the clouds are of the cumulus or cumulo-nimbus type.

Figure 24 shows a well-developed polar-front wave over the United States, while figure 25 gives a typical example of a whole family of wave disturbances on a polar front extending in a southwesterly-northeasterly direction over the eastern part of the United States.

It has already been brought out that in the course of the life history of a polar-front wave, the horizontal amplitude of the wave increases, while at the same time the cold front gradually overtakes the slower moving warm front. This process is illustrated through the successive stages represented in figure 26. At the end of this process, when the cold front has finally reached the warm front, the warm section of the wave has been lifted to higher levels, and the cold air has spread out over a larger area next to the ground. Thus cold and warm air masses originally lying side by side are through this process rearranged in a more stable position, with warm air above and cold air below. Through this rearrangement, potential energy is released and converted into kinetic energy. The shallow layer of cold air brought

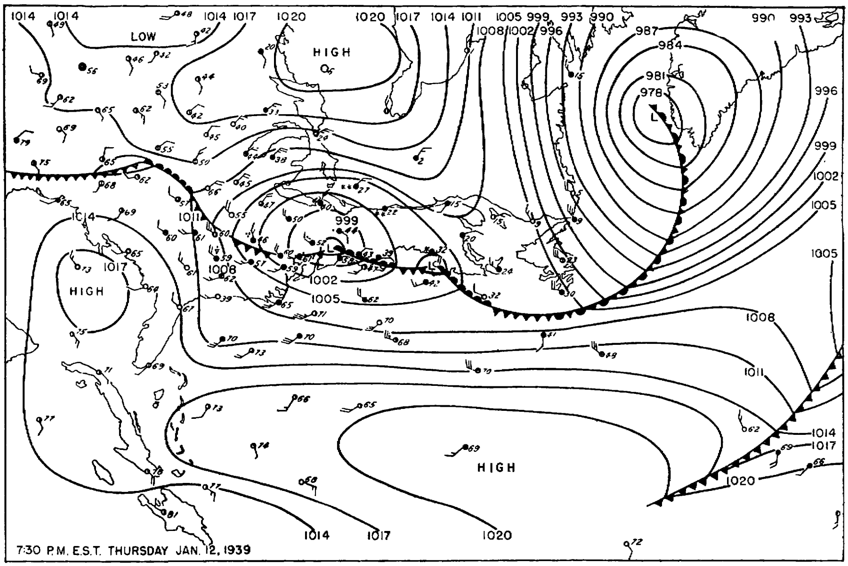

FIGURE 25.—An example of a family of waves on a frontal zone extending from the Gulf of Mexico to Greenland during a period of weak circulation. The symbols used are the same as those in figure 24. (From (*10*).)

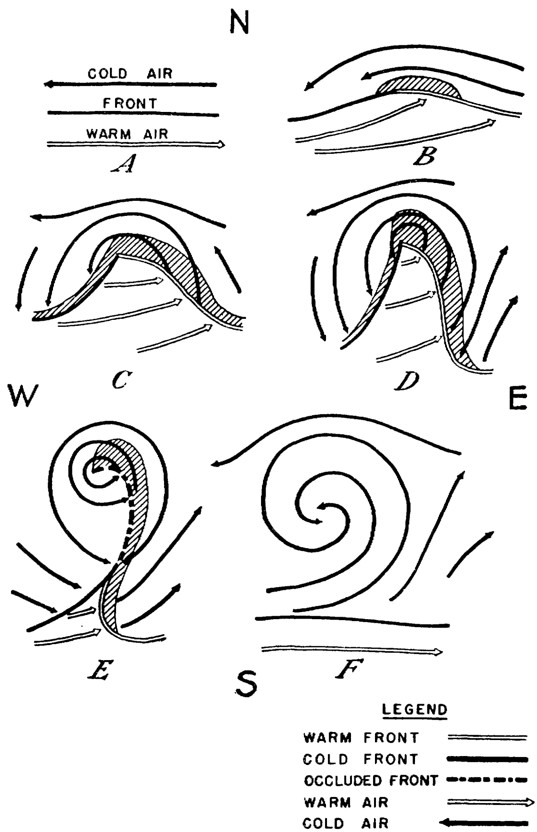

FIGURE 26.—Schematic horizontal representation of the gradual development and ultimate occlusion of a polar-front wave. (From (*10*).)

southward and eastward through this process is eventually warmed and transformed into subtropical air, capable of rising over the next outbreak of cold polar air.

A polar-front wave is said to occlude when its cold front finally completely overtakes the warm front, and the process itself is referred to as an occlusion. The occluded waves have a tendency to gravitate into the large-scale semipermanent cyclonic centers of action, such as the Aleutian and Icelandic lows.

SUMMER CIRCULATION PATTERNS

As has been shown, the northern polar front during the winter season tends to bulge southward over the continents, in response to the intense production of cold air over the large snow-covered land masses in high latitudes. In summer the situation is to some extent reversed. Over the major portion of these land areas the snow cover disappears, and the temperature rises above that prevailing over the ocean areas. Because of the high elevation of the sun and the long days in high latitudes, the rate of production of polar air falls off, and

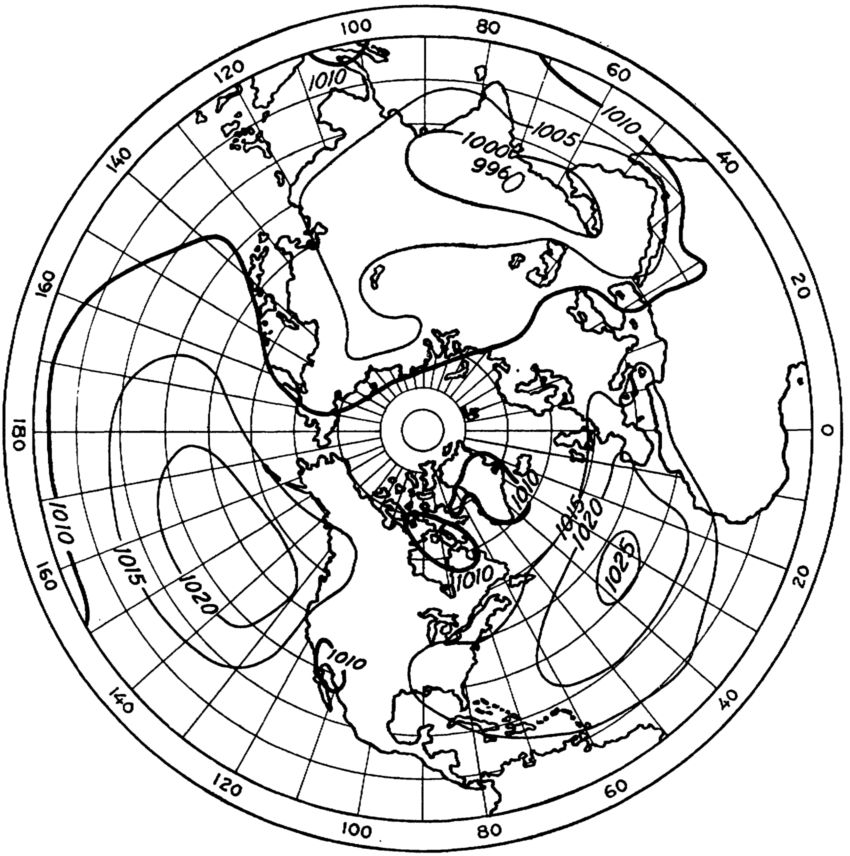

FIGURE 27.—Normal sea-level-pressure distribution (millibars) over the Northern Hemisphere in July. (From (*21*).) Compare this with figure 7 and note the complete disappearance of the Aleutian low. The Icelandic low is now very weak, and the Asiatic high has been replaced by relatively low pressure. Note the well-developed oceanic highs characteristic of the summer season.

the temperature contrast between high and low latitudes diminishes. Thus the contrast between air masses also diminishes, and the polar front recedes northward. There is now a tendency for the polar front to bulge northward over the continents and southward over the oceans.

During the winter the meridional temperature contrast dominates and determines the broad features of the circulation pattern. The winter temperature contrast between land and ocean serves, in the main, to accentuate this meridional contrast. During the summer season, on the other hand, the meridional temperature gradient is so weakened that the temperature contrast between land and ocean areas tends to become the dominating factor, to a considerable extent opposing the normal meridional temperature contrast. As a result, widespread but slow-functioning plants for cold-air production are established over the northern oceans.

Just as the cold air produced in polar regions during the winter season spreads southward and in so doing acquires an anticyclonic rotation (east wind) around the polar air dome, so the slowly spreading air from the summer maritime cold-air plants assumes a clockwise rotation around the ocean basins. Since pressure and wind always tend toward a mutual adjustment, it follows that the northern oceans will be dominated by large high-pressure areas (fig. 27). Above these high-pressure areas there must be a compensating inflow from the continents.

It is not possible at present to apply successfully the previously developed concept of planetary flow patterns to the summer circulation problem. Because of the reduced temperature contrasts characteristic of this season and the resulting weaker winds it is probable that weather then is much more completely dominated by local factors. For these reasons the following discussion will be restricted to the circulation over the North American Continent during the warm season.

The meridional temperature contrast over this continent practically disappears south of latitude 45°. The principal polar front normally extends west-east somewhere in the vicinity of the Great Lakes. Apart from occasional inundations with rapidly warming polar air, the United States is covered with a blanket of tropical air and its weather is consequently to a large extent dominated by processes occurring within this air mass.

The prevailing motion in the warm air over the United States and south of the polar front consists in a drift eastward, strong in the north and decreasing in intensity southward, until it practically vanishes at about latitude 30°. This wind distribution is strongly suggestive of the frictional mechanism for the maintenance of the westerlies in middle latitudes discussed previously. It thus appears that the eastward drift of the air over the United States may be explained as the result of drag exerted by the somewhat stronger west winds prevailing over the polar front farther to the north, an explanation which is strengthened by the fact that the absence of horizontal temperature contrasts indicates that there are no wind-energy sources to be found in the central and southern parts of this country.

The wind energy brought in from the north must undergo an incessant decay and dissipation. Such a decay must be associated with a breaking up of the wind currents into eddies of varying diameters. It will be shown later that this is actually the case and that the lower troposphere is characterized by the frequent formation of clockwise (anticyclonic) vortices which tend to remain stagnant or to drift slowly eastward across the continent. These quasi-horizontal eddies are not so clearly established next to the ground, and thus it becomes necessary to make use of the upper-air data for their study.

It has been brought out previously that the free atmosphere everywhere is losing heat by radiation. This loss is, however, small and widespread, probably of the order of magnitude of 1° or 2° C. a day. Thus, if one wants to follow an individual parcel of air over short periods of time it is permissible to assume that its movement takes place without change in realized heat content (barring condensation of water vapor). A good way of expressing the heat content of a parcel of air is to indicate the temperature that this parcel would have if it were compressed, without gain or loss of heat, to a standard (sea level) pressure. This temperature is called the potential temperature of the air. It is possible to compute the potential temperature of any air parcel the actual temperature and pressure of which are known. When this is done it is found that the potential temperature normally increases upward in the atmosphere (about 4° to 5° C. per kilometer in the lower troposphere; somewhat more rapidly higher up). It follows from the definition of potential temperature that for a constant pressure it increases with the actual temperature. Thus the potential temperature normally increases southward.

If one now plots, for a number of points in the United States, the height above sea level where a certain potential temperature is found, it becomes possible to construct a topographic chart for a surface of constant potential temperature in the atmosphere. Such a surface (also called an isentropic surface) is normally found to slant downward from north to south. Since potential temperature normally increases upward along the vertical, it follows that the higher isentropic surfaces are characterized by a higher potential temperature than the lower ones. If, for a given occasion, a set of such charts is prepared for different surfaces, it is possible to prepare a vertical cross section through the atmosphere to describe the potential temperature distribution. A mean cross section of this type is given in figure 28, in which the broken lines (isentropic lines) indicate the intersection with the individual isentropic surfaces. This diagram brings out the fact that

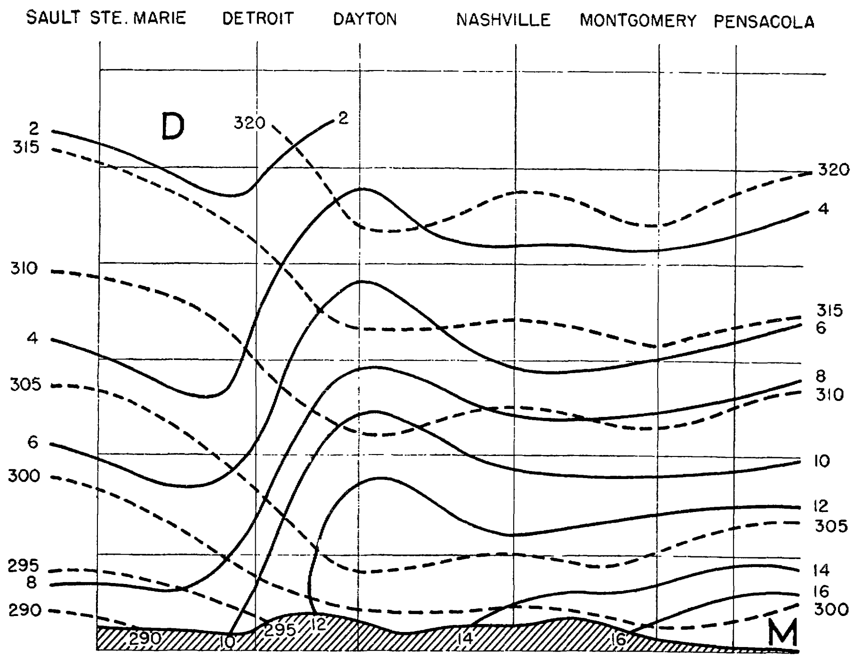

FIGURE 28.—Mean vertical section between Sault Ste. Marie, Mich., and Pensacola, Fla., August 1936. Horizontal lines are drawn for intervals of 1 kilometer, broken lines represent potential temperature (in °C. Abs.), and full lines specific humidity (in grams of water vapor per kilogram of moist air). (From (*19*).) Note constancy of potential temperature (and hence ordinary temperature) from Dayton southward. (D indicates dry air; M, moist air.)

during the summer, when the temperature itself does not vary greatly from north to south, the isentropic lines (and surfaces) are fairly horizontal, except far to the north.

The significance of the isentropic surfaces lies in the following:

As long as parcels of air move without appreciable change in heat content, they must remain within one and the same isentropic surface. Thus, to the extent that this assumption is fulfilled, it can be said that by studying charts of the same isentropic surface for 2 consecutive days, it is reasonably sure that the same parcels of air are being dealt with. This would not be the case if charts for fixed upper levels were studied, since air may rise or sink through a fixed horizontal plane.

To identify the individual parcels of air in a given isentropic surface, use can be made of their moisture content, expressed as a weight ratio between water vapor and air per unit mass of moist air. This ratio (specific humidity) does not change except as the result of condensation or evaporation, or as the result of mixing with air of a different specific humidity. By drawing lines of constant specific humidity in a surface of constant potential temperature, a method of "tagging" and identification of air parcels is reached.

It is important to know whether air is moving up slope or down slope in the isentropic surface. Up-slope motion may lead to condensation, and in that case the realized heat content increases so that the air must climb toward a surface of higher heat content (higher potential temperature). To study the motion in a given isentropic surface, one may plot on the chart for that particular surface wind directions and wind velocities as obtained by interpolation from pilot-balloon observations and compare the resulting pattern of motion with the pattern of the contour lines. The final isentropic chart should thus contain specific-humidity lines, contour lines, and winds.

A study of daily isentropic charts for the summer season reveals that the free air circulation over North America is dominated to a very large extent by large anticyclonic vortices. The accompanying chart for June 27, 1937, furnishes a beautiful illustration (fig. 29).

In this case, strong westerly to northwesterly winds prevail from the Great Lakes eastward. Possibly as a result of frictional drag from this strong wind system a tongue of moist air has been brought in over the United States, extending from Arizona toward Illinois and Indiana, from then on curving anticyclonically southward and finally southwestward toward the Gulf coast. A tongue of dry air is sliding southward and downhill from New England, winding itself clockwise around the moist air. The movement of this dry air must be accompanied by a certain amount of vertical shrinking and horizontal stretching to permit it to assume the clockwise trajectory indicated on the chart. Practically all isentropic charts for the summer months contain examples of such spiraling interaction between moist and dry tongues, and normally the spiraling motion has a clockwise direction. As might be expected the moist tongues form troughs and the dry tongues ridges in the contour patterns.

Thunderstorms and convective activity are most likely to occur in the moist tongues where the supply of water vapor is adequate, particularly on the left side of the axes of the moist currents (facing downstream). Convective vertical currents may, of course, develop anywhere as a result of intense surface heating, but in those regions where the convective towers shoot up into an overlying dry stratum, lateral mixing processes will soon deplete the cloud masses of their moisture, whereas the development can proceed unhindered in regions where the moisture content aloft is high. Figure 30 shows the path of the center of maximum thunderstorm activity during the same general period from which figure 29 was taken. This path shows a characteristic anticyclonic trajectory very similar to the one suggested by successive isentropic charts for the entire period, and it emphasizes the significance of isentropic charts for summertime rainfall forecasting.

The clockwise eddies referred to above are so characteristic of our summer circulation and so slowly changing that they may be found also in mean isentropic charts for longer periods. Figure 31, *A* and *B*, gives the mean insentropic charts for the months of August 1935 and August 1936. It is seen that both charts indicate the presence of large anticyclonic eddies; that for 1935, which probably comes fairly close to normal conditions, is characterized by two eddies—one moist tongue entering the United States from the southwest over Arizona and a second entering from the south over western Florida. In 1936 there was only one large eddy, with a large dry

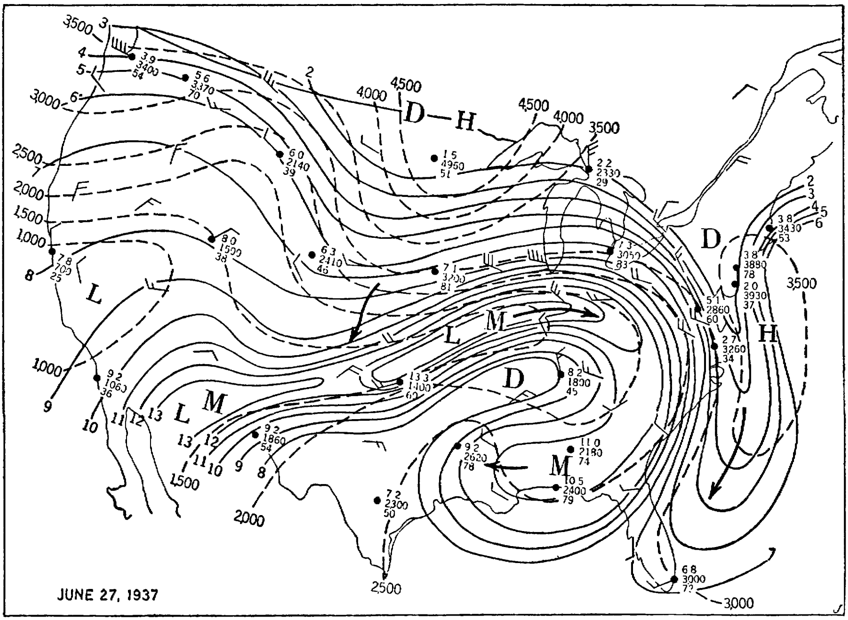

Figure 29.—Typical anticyclonic eddy formation of a moist tongue in an isentropic surface. This chart is drawn for a potential temperature of 310° Abs. Broken lines represent contour lines (height above sea level) and indicate 500-meter intervals. Constant specific-humidity lines (full lines) represent intervals of 1 gram of water vapor per kilogram of moist air. To the right of the station dot are figures indicating the observed specific humidity (top), the height of the surface (center, in meters), and the relative humidity (bottom). Winds are entered in the same manner as in figure 24. M represents a tongue of moist air; D, of dry air. H indicates high level of isentropic surface; L, low level. Arrows show directions in which the different tongues have been moving during the last 24 hours. (From (*17*).)

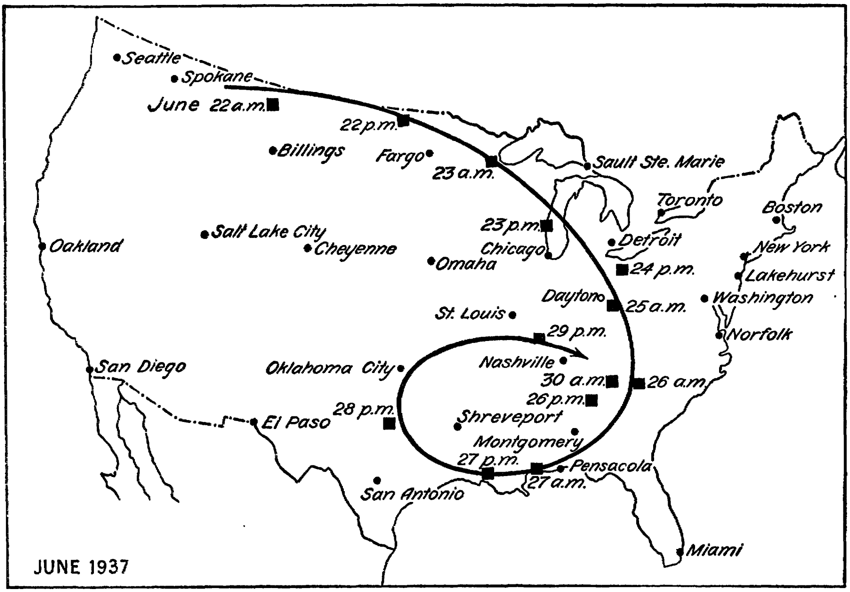

FIGURE 30.—Trajectory of the center of maximum thunderstorm activity following the invasion of a tongue of moist air aloft and positions of upper-air sounding stations used in this analysis (dots). The black squares mark the successive positions of the center of thunderstorm activity for the 12-hour periods preceding the dates (in June 1937) entered beside them; these were fixed with the aid of thunderstorm reports and 12-hourly amounts of precipitation. (From (*14*).)

current sweeping downhill from the north over the Great Lakes region. The persistence of this large dry tongue aloft is associated with the severe drought of that year in a large part of the Middle West.

APPLICATIONS TO LONG-RANGE FORECASTING

It is, of course, impossible to utilize effectively the results set forth above as long as the mechanics and thermodynamics of the changes in circulation intensity which cause, or are associated with, the observed changes in the mean circulation patterns are not understood. These changes are generally fairly slow; it has already been pointed out that in winter the normal time interval between two consecutive peaks of circulation intensity is about 6 weeks. Thus the circulation-intensity trend is likely to persist from one week to the next, and this persistence tendency has a definite forecasting value. The same applies to the persistence which may be observed in the gradual displacements of the centers of action. It should not be forgotten that so far even our daily forecasts are obtained through a technique which essentially makes use of persistence tendencies of various kinds rather than of thoroughly understood dynamic and thermodynamic calculations. Modern daily forecasting terminology often suggests an intimacy with the physical processes of weather which sometimes is more wishful than real.

If it is possible to predict with some degree of success, 1 week in advance, the position and development of the principal centers of action, it also becomes possible to predict the position of the principal frontal zones and hence of the prevailing storm tracks. A forecasting technique based on the study of the behavior of the centers of action is obviously not going to help in predicting, for any given locality, the sequence of weather day by day a week in advance, but it does offer the opportunity to tell whether the mean temperature in a certain region is going to be above or below normal and whether the rainfall will be light, moderate, or heavy in terms of the normal rainfall intensity.

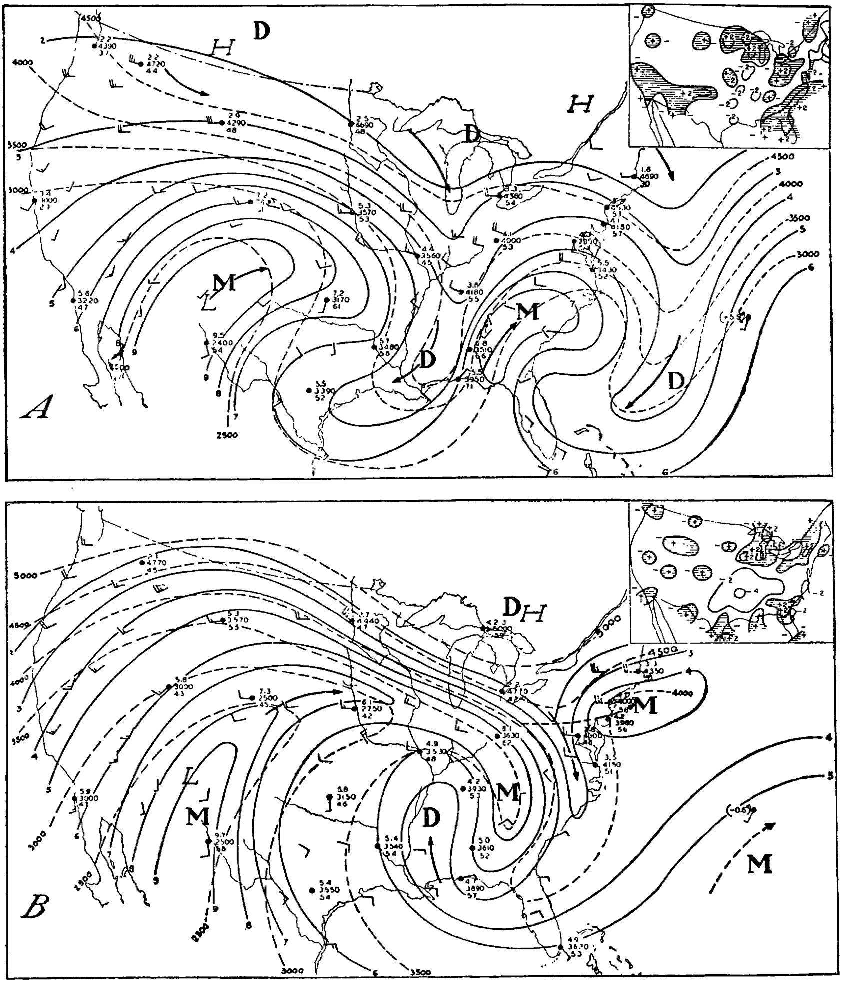

FIGURE 31.—*A*, Mean isentropic chart for August 1935. Symbols and notations are the same as in figure 29. *B*, Mean isentropic chart for August 1936. Note precipitation deficiency in the Middle West under the dry portion of an anticyclonic eddy. (Insets, departures of precipitation from normal, expressed in inches.) (From (*24*).)

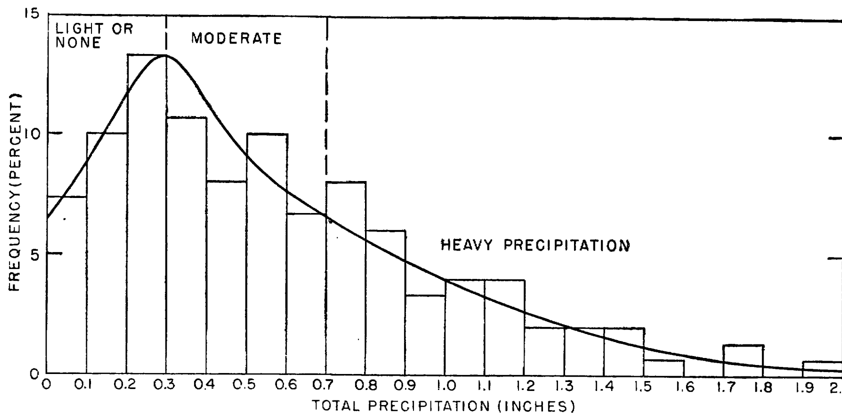

FIGURE 32.—Normal frequency distribution of accumulated 5-day rainfall for Iowa in August. Areas of light, moderate, and heavy precipitation are of equal size.

An experiment in 5-day forecasting of temperature and rainfall anomalies, based on such studies of the behavior of the centers of action in the atmosphere, has recently been organized as a joint undertaking between the Department of Agriculture, the Weather Bureau, and the Massachusetts Institute of Technology. In view of the fact that the technique employed will probably find increased applicability during the next few years, it seems appropriate to devote some space to a description of this project.

The project leaders are well aware of the fact that the technique used in daily forecasting cannot very well be extended to periods much in excess of 2 or possibly 3 days. Even if the forecaster should have a perfectly correct concept of the anticipated weather sequence, a slight error in his timing of the events would soon throw the forecast out of line with the observed weather. It is therefore necessary to treat the 5-day forecast problem as a statistical one, particularly in view of the fact that a statistical technique based on the ideas set forth above might perhaps eventually be extended to cover even longer forecast periods (two, or as a possible upper limit, three weekly or 5-day intervals), which obviously would be impossible on the basis of the technique used in daily forecasting.

As a first step in this development, a statistical study has been made of the normal character of the 5-day mean temperatures and accumulated 5-day rainfall intensities in the United States, and the results have been expressed graphically in the form of frequency curves. These curves represent, specifically, for a given region and a given season (month), the frequency of different departures from normal of the 5-day mean temperature, and likewise the frequency distribution of accumulated 5-day rainfall amounts for different regions and seasons. Both types of curves are prepared, not from records of a single station, but from State averages, and they are based on roughly 50 years of data. These curves are probably adequately representative of a State as a whole in open country such as the Mississippi Valley, but they are definitely inadequate in the mountainous regions, where the climatic characteristics vary sharply from point to point.

The rainfall-frequency curves (fig. 32) are, of course, highly asymmetric, since there is no such thing as negative rainfall. The area under the curve in this figure may be divided into three equal parts, which might be labeled "none or light," "moderate," and "heavy" precipitation. It is evident from these definitions that all three types of precipitation have equal chance probability (one-third). It is also evident that the rainfall values giving the boundaries between light and moderate and between moderate and heavy precipitation vary from one part of the country to another, being much lower in the arid West than in the East.

The temperature-frequency curves (fig. 33) are fairly symmetric. The area under the curve in figure 33 may be divided into five parts, a portion (25 percent) around the normal labeled "nearly normal," another portion labeled "below normal" (25 percent), a third portion labeled "above normal" (25 percent), and two extreme portions of 12.5 percent each named "much below normal" and "much above normal," respectively. Also here the numerical values of the various demarkation lines vary from region to region, since the frequency curve has a small spread in a maritime climate and a large spread in a continental climate. The normal 5-day mean temperature itself varies of course from station to station and from day to day throughout the month, but there is good reason to believe that the frequency distribution of departures from normal in climatologically homogeneous regions changes only slowly from point to point and from day to day.

Through the statistical analysis just described it is possible to incorporate, in the definitions and terminology used in the 5-day forecasts, the climatological characteristics of each particular district in the United States. The forecaster's problem is reduced to the task

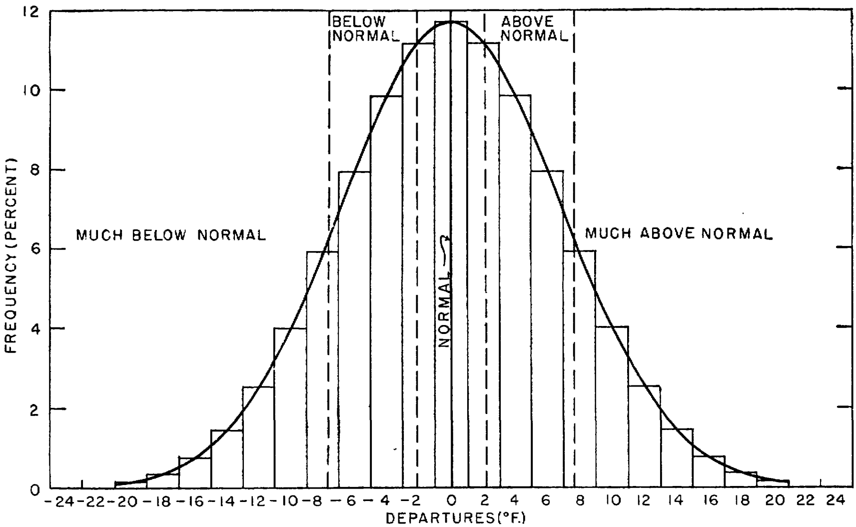

Figure 33.—Normal frequency distribution of different departures from normal of 5-day mean temperatures for Iowa in August. Areas marked below normal, normal, and above normal are of equal size (each one-fourth of total), and the two extreme areas are likewise equal (each one-eighth of total).

of determining from the current weather charts and for each 5-day period the regions in which the rainfall will be light, moderate, or heavy and the regions in which the temperatures will be much below normal, above normal, etc. Through the choice of definitions introduced he has been spared the necessity of keeping in mind the climatic characteristics of each portion of the country. If desirable, it is of course possible, once the forecast has been completed, to translate the predicted anomaly distributions roughly into actual degrees of departure from normal and into actual amounts of precipitation.

On the basis of the definitions introduced, it is evident that in a long series of charts of the observed 5-day anomaly distribution, areas of light, moderate, and heavy rainfall should be equal, and similar considerations apply to the areas of different observed temperature departures.

The actual forecasting technique is based entirely on the use of prognostic charts. The first step consists in the construction of a mean sea-level-pressure chart for the United States for the coming 5-day interval. In the construction of this chart, the principal guidance is furnished by the past behavior of the circulation index and of the large centers of action. The main problem is to decide whether the circulation intensity is going to increase or decrease; as yet this question has to be answered largely on the basis of persistence tendencies.

The next step is to construct a prognostic pressure chart for the 3-kilometer level over the United States.

Because of the lack of upper-air data from the surrounding oceans, it is not generally possible to base the preparation of this chart on continuity of trends, and other cruder guiding signs have to be used. With increasing circulation, the north-south amplitudes of the isobars at 3 kilometers tend to decrease; with decreasing circulation they increase. Furthermore, there are certain characteristic 3-kilometer-pressure patterns which normally occur with maximum and minimum circulation (figs. 17 and 18). This part of the procedure is as yet extremely uncertain and awaits additional upper-air data from the oceans before substantial improvements can be expected.

Quite recently a procedure has been developed which permits determination by extrapolation of the pressure at the 3-kilometer level from the observed pressure and temperature at sea level. The procedure is applicable only over the oceans and specifically only in those regions where strong winds or shower activity give indications of intense vertical stirring, so that the vertical temperature-lapse rate may be estimated. Through this procedure it is now possible to draw reasonably adequate 3-kilometer-pressure charts for the entire region between 30° and 170° west longitude, thus including large portions of the Atlantic and the Pacific. With the aid of consecutive-mean charts of the observed pressure distribution over this large area the problem of drawing prognostic mean 3-kilometer-pressure charts for the United States has come much closer to being a practical routine operation than before.

During the warm half of the year a prognostic mean isentropic chart is constructed, mainly on the basis of the slowness of and continuity in the evolution of the isentropic flow patterns.

The three charts obtained thus far are not independent of each

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other. If the pressure distributions at sea level and at 3 kilometers are known, the mean temperature between these two levels is prescribed. The resulting horizontal distribution of the 5-day mean temperature for the lowest 3 kilometers must not depart too much from the normal north-south temperature contrast in the atmosphere and must be compatible with the prognostic isentropic chart, since temperature and moisture content are fairly intimately correlated. These considerations and other similar cross checks of the prognostic charts serve the extremely important purpose of insuring internal consistency in the anticipated mean state of the atmosphere, and therein lies the principal scientific achievement of this forecasting project. The prognostic charts are modified until such consistency is obtained.

It then becomes possible to draw prognostic charts of temperature and rainfall anomalies for the coming period; in this work full use is made of the locations and movements of the principal frontal zones as indicated by the prognostic pressure-distribution charts and of indications concerning the availability of moisture furnished by the prognostic isentropic chart.

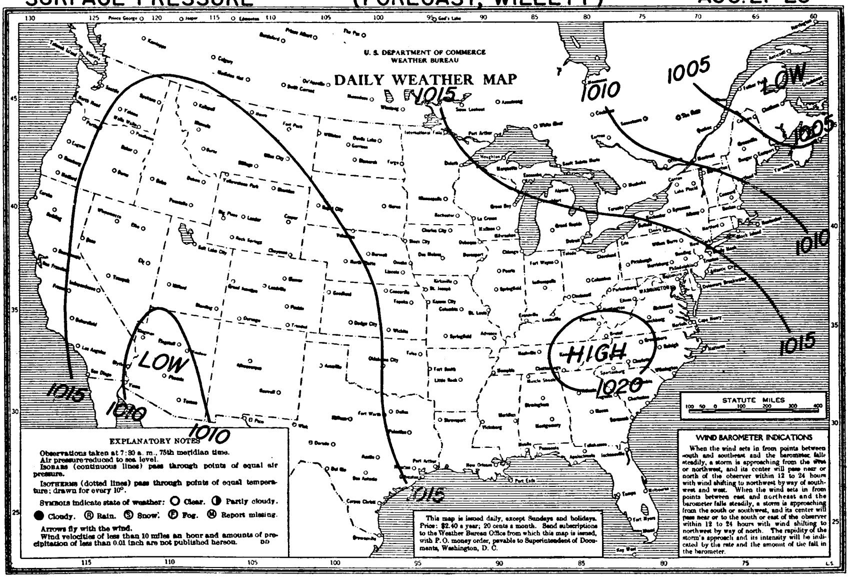
Figures 34–38 contain the prognostic and verification charts for one of the first periods treated by this technique. Real difficulties are encountered when the rainfall is of a convective character and hence very spotty in its occurrence. The particular forecast illustrated in figure 37 is satisfactory over the major part of the country, but it exhibits two definite errors, one of them the extension into Montana of the heavy rainfall forecast and the other the omission to forecast the heavy rainfall which actually occurred over a small portion of the middle Atlantic coast. More intense stress on the need for consistency between the various prognostic charts would have reduced the magnitude of these errors.

It should be added that mistakes in timing might easily affect this type of forecasting also. If an error is made in the timing of the displacement of the centers of action, the anticipated rainfall or temperature patterns may be correct in their general character but incorrectly placed on the map, resulting, obviously, in a failure of the forecast in certain regions.

The principal advantage of the procedure outlined above lies in the fact that it helps to insure consistency and permits the forecaster to incorporate into his picture of the coming atmosphere, step by step, every prognostic indication at his disposal. The human mind has a limited capacity, and as long as forecasting is done in the head, from inspection of a great and bewildering mass of data, it is more than likely that for each new indication considered, an earlier indication is dropped and forgotten. This danger is reduced through the introduction of the engineering procedure outlined above.

For agriculture, flood control, water supply, and many other interests, quantitative forecasts are of tremendous potential value. The technique outlined above represents a crude first step toward such quantitative forecasting, and it is therefore certain to be further developed in the years to come.

SURFACE PRESSURE (FORECAST, WILLETT) AUG. 21-25



SURFACE PRESSURE (OBSERVED) AUG. 21-25, 1940

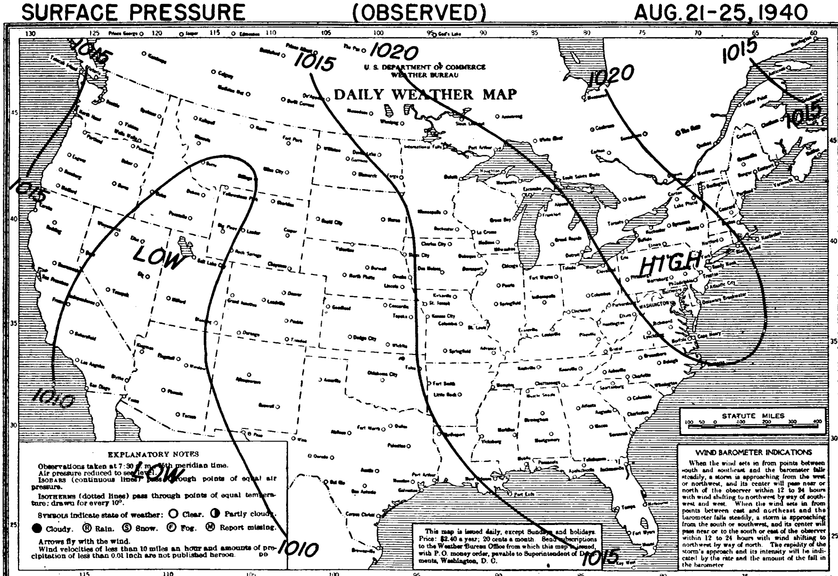
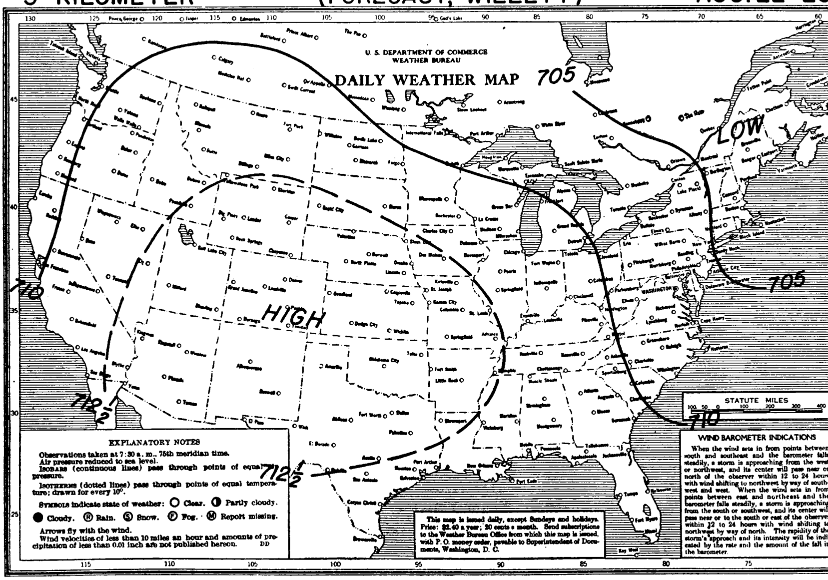


FIGURE 34.—Forecast and verification charts of mean sea-level-pressure distribution (millibars) over the United States for the period August 21–25, 1940, prepared on daily-weather-map forms.

3-KILOMETER (FORECAST, WILLETT) AUG. 22-26



3-KILOMETER (OBSERVED) AUG. 22-26

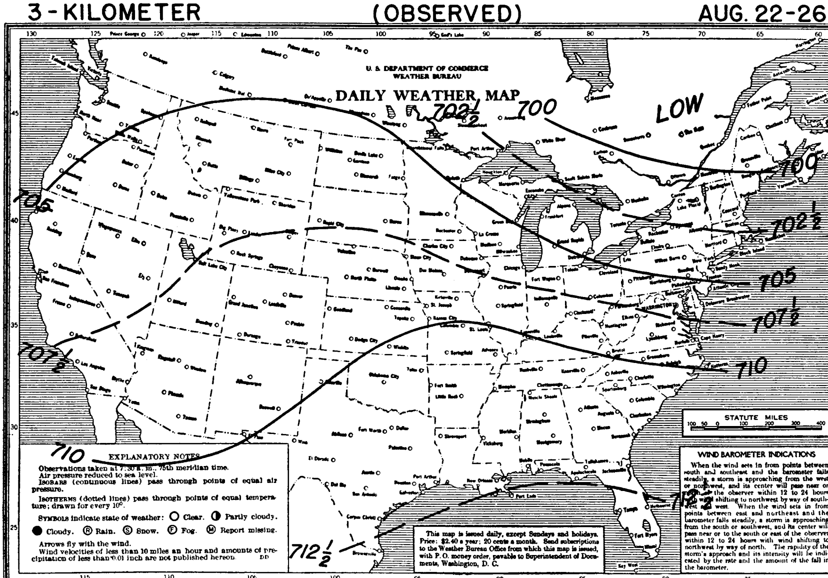
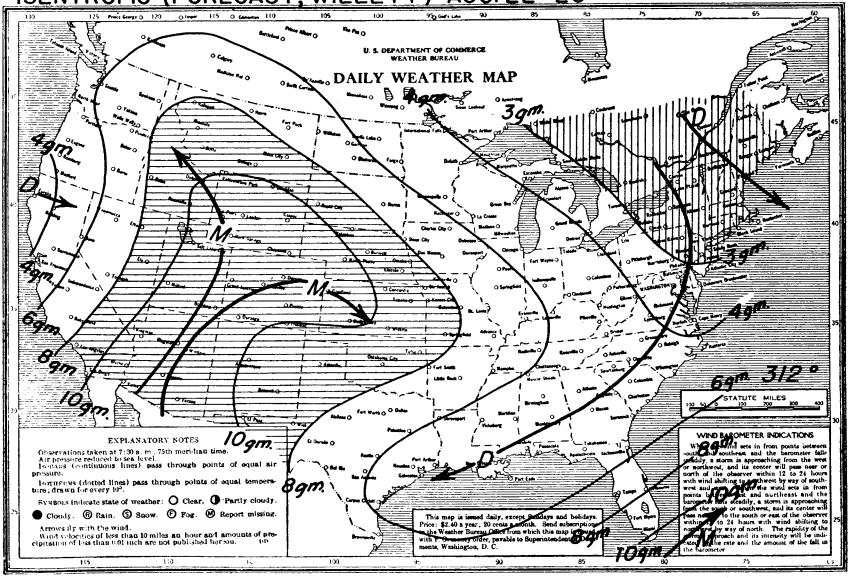


FIGURE 35.—Forecast and verification charts of mean 3-kilometer-pressure distribution (millibars) over the United States for the period August 21–25, 1940.

ISENTROPIC (FORECAST, WILLETT) AUG. 22-26



ISENTROPIC (OBSERVED) AUG. 22-26

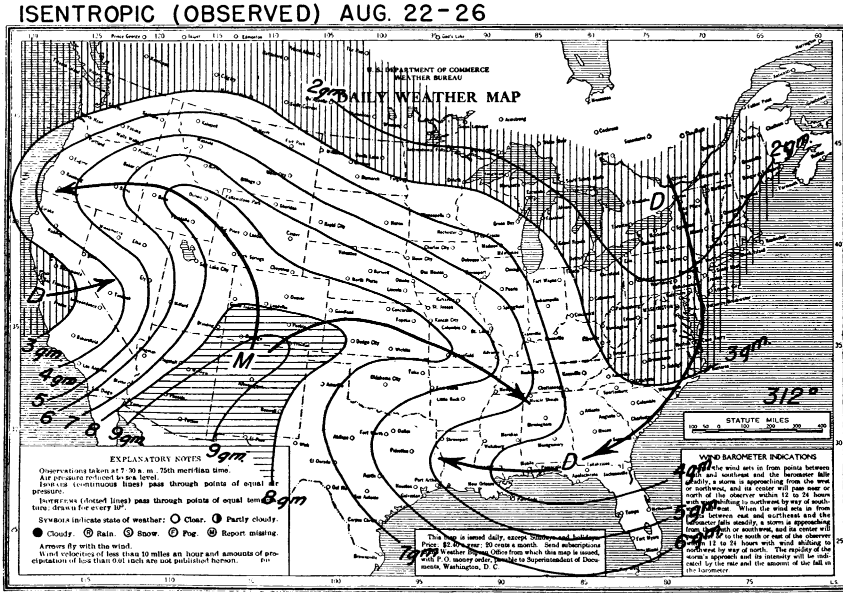
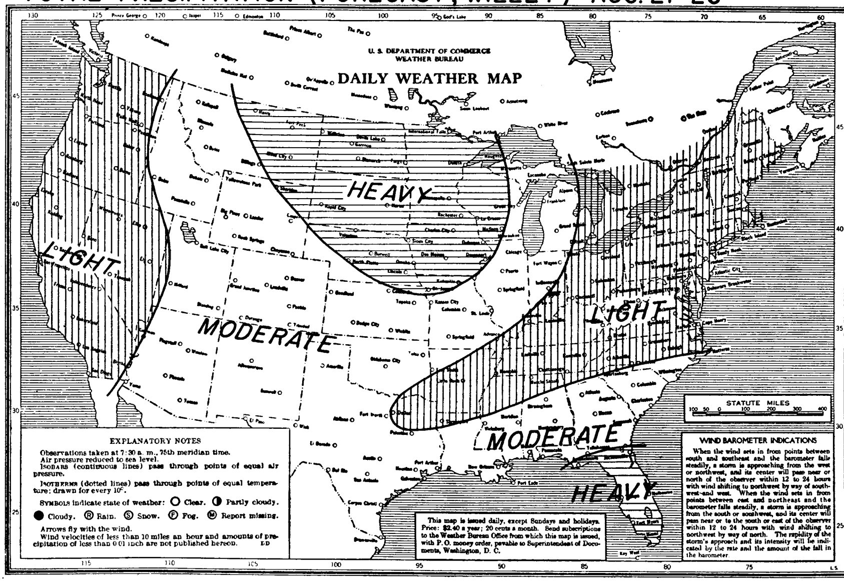


FIGURE 36.—Forecast and verification charts of the mean isentropic-moisture distribution over the United States for the period August 21–25, 1940.

TOTAL PRECIPITATION (FORECAST, WILLET) AUG. 21-25



TOTAL PRECIPITATION AUG. 22-26, 1940

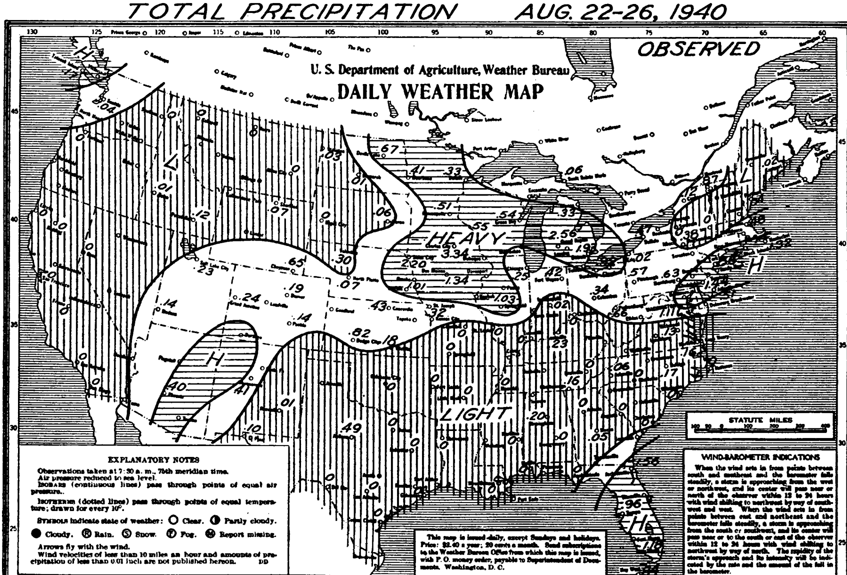
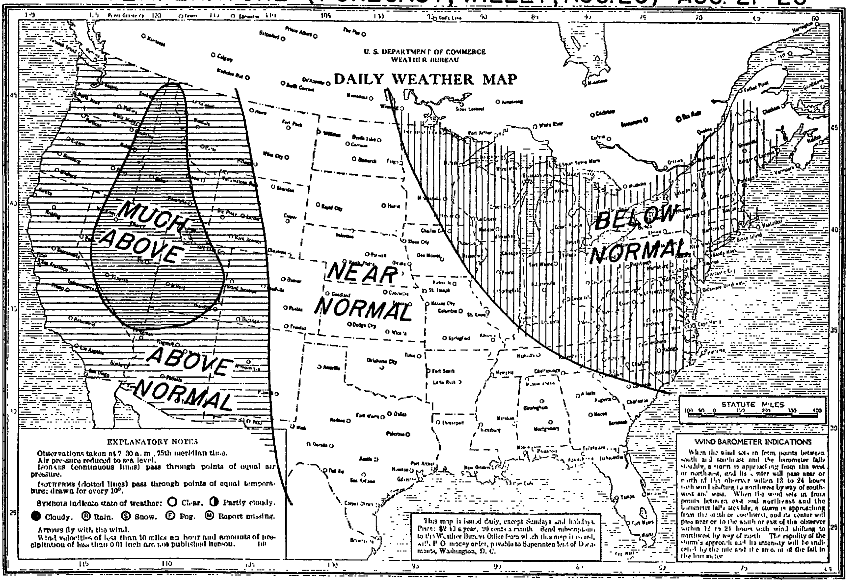


Figure 37.—Forecast and verification charts of accumulated-rainfall distribution for the period August 21–25, 1940.

MEAN TEMPERATURE (FORECAST, WILLET, AUG. 20) AUG. 21-25



TEMPERATURE DEPARTURE AUG. 22-26, 1940

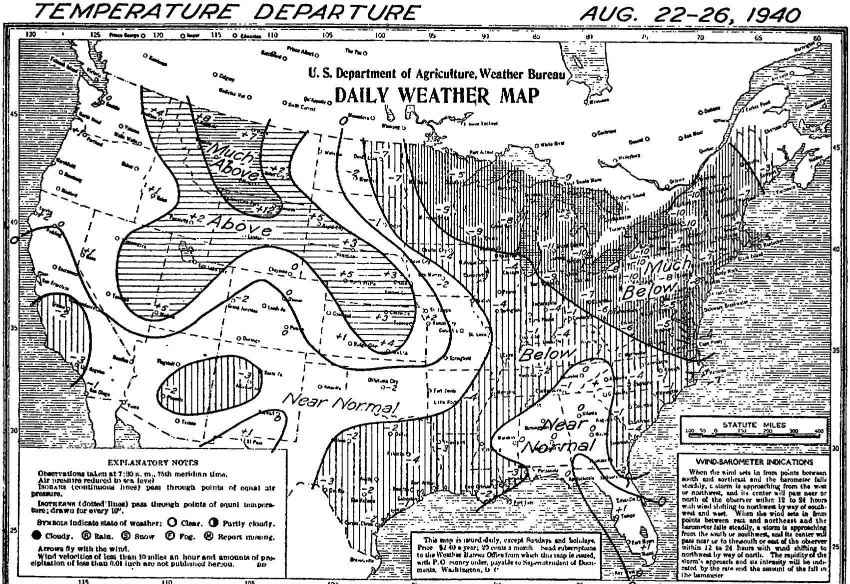


FIGURE 38.—Forecast and verification charts of mean temperature anomalies for the period August 21-25, 1940.

HISTORICAL NOTES

The brief notes given below do not in any sense constitute an attempt to trace the history of the growth of our knowledge concerning the atmosphere, as may be seen from the fact that there are a number of basic meteorological discoveries to which no reference is made. The single purpose of these notes is to attempt to trace the origin of the principal ideas which the writer has sought to weave into a coherent picture of the atmosphere as a mechanical and thermodynamic machine that responds in a predictable fashion to specific external influences.

The German physicist Von Helmholtz took a great deal of interest in meteorological problems. His two papers in 1888 on atmospheric motions, translated into English and published by Cleveland Abbe (*1*), contain a remarkably modern picture of the circulation of the atmosphere. In his analysis, Von Helmholtz considered the atmosphere as consisting of a number of flywheels, or rings of air, spinning around the earth's axis in different latitudes. He realized that the energy of this flywheel motion comes from superimposed slow meridional circulations set up as a result of the inequality in solar radiation income between low and high latitudes. He also recognized that frictional forces, both along the earth's surface and in the free atmosphere, are needed if the thermally driven meridional circulation and the flywheel circulation are to be maintained at a constant speed.

Von Helmholtz was apparently aware of the important role played by surfaces of discontinuity in the atmosphere and gave an elaborate dynamic theory for the intermittent generation and destruction of the polar front, without actually introducing this term. His polar front extended along a latitude circle. Considerable time was devoted by Von Helmholtz to the study of wave motions in atmospheric surfaces of discontinuity, but the waves analyzed by him have a length of up to a few kilometers and should not be confused with the observed cyclonic polar-front waves. He also derived an expression for the equilibrium slope of the polar front as a function of the temperature and wind discontinuity between the two air masses separated by the front. He may be regarded as a very early forerunner of the modern meteorological school.

In Von Helmholtz's day, the synoptic charts contained so few and such scattered observations that it was obviously impossible to give direct evidence for the existence of discontinuities in either wind or temperature. Nevertheless, the theory for such discontinuities continued to attract the attention of theoretical meteorologists, and the Austrian meteorologist Margules (*12*) finally established the equilibrium condition for a front of arbitrary orientation.

The squall line (nowadays called the cold front) was fairly well known from observations at an early stage, but it was not until the World War came along with its demand for improved meteorological service that the Norwegian meteorological school, headed by V. Bjerknes, actually had at its disposal a network of stations sufficiently dense (though of very limited extent) to permit the discovery of both cold front and warm front as elements of the ideal cyclone model (*4*). From then on a rapid development took place. The life history of cyclones culminating in the occlusion process and the characteristic properties of the different air masses interacting in a polar-front wave were discovered by the Norwegian meteorologists, J. Bjerknes and H. Solberg, and by the Swede, Bergeron (*5*). It is very difficult to separate their individual contributions since they worked in close harmony. This theory now serves as the principal basis for daily forecasting.

The break-down of the symmetrical polar front into branches extending generally from southwest to northeast was clearly indicated as an empirical fact fairly early in the writings of the Norwegian school (*6*). Bergeron (*3*) likewise recognized as an empirical fact the existence of a reverse cell in the meridional circulation of the atmosphere, without being able to offer any explanation. The recognition that such a cell must exist to serve as a necessary brake on the general circulation of the atmosphere came from the Massachusetts Institute of Technology school of meteorologists, where also the first attempts were made to compute physically reasonable models for the statistical mean meridional circulation (*17*). In these attempts the role of large-scale lateral mixing processes in diffusing momentum northward or southward was first recognized in modern times, although Von Helmholtz's papers actually contain references to the possible significance of such processes.

Sir Napier Shaw (*20*) was the first to advocate the use of isentropic charts, but the first synoptic isentropic charts were drawn at the Massachusetts Institute of Technology (*16*), and it was there that specific humidity was introduced as a quasi-conservative element useful for tagging and identifying air masses. These isentropic-humidity charts in time led to the analysis of the free-air, anticyclonic eddy patterns which dominate our summer weather, and to the development of a dynamic theory of the maintenance of the eddies (*19*).

The break-down of the zonal circulation into horizontal cells or centers of action has, of course, been known as long as world-wide synoptic charts have been available. The dynamic theory for the large-scale planetary flow patterns was developed at the Massachusetts Institute of Technology (*18*), where the relation between the size of these patterns and the zonal circulation intensity was discovered.

The first systematic attempts to utilize the circulation model presented in this paper in the preparation of 5-day forecasts were made by Willett and his collaborators (*2*). The principal advocate of the introduction of engineering techniques in forecasting is the Norwegian meteorologist Petterssen (*15*), whose work along that line has led to the development of several important aids to our synoptic forecasting technique. In this country the use of prognostic charts as a tool in forecasting has been strongly advocated by Prof. H. Byers, of the University of Chicago. The systematic procedure described in this article for the construction of reasonably complete three-dimensional prognostic models of the atmosphere was developed at the Massachusetts Institute of Technology and is still in its infancy.

Our knowledge of the atmospheric radiation processes is of a later date. Taking into account the fact that the atmospheric water vapor is practically transparent to solar radiation but nearly opaque to the long heat radiation from the ground, Emden (*8*), through theoretical studies, made it plausible that radiation alone would produce a highly unstable lower troposphere characterized by a rapid vertical temperature drop upward, and a nearly isothermal stratosphere. Before him, Humphreys (*11*) and Gold (*9*) had given fairly reasonable explanations for the temperature of the stratosphere. Simpson (*22*, *23*) was the first to compute the vertical transfer of radiation in the atmosphere under actually observed temperature conditions, taking into account the selective character of water-vapor absorption. A German meteorologist, Möller (*13*), was the first to state clearly that the free atmosphere practically everywhere must be considered as a cold source with respect to purely radiative processes, a conclusion which necessitated a thorough revision of certain earlier theories for the general circulation of the atmosphere. The principal work on the determination of the absorption coefficients of water vapor is now carried on at the California Institute of Technology by Elsasser (*7*). Until these coefficients have been carefully determined, our ideas concerning the general circulation must remain fairly speculative.

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